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ENGINEERING CONSIDERATIONS IN AUTOMATIC EXPOSURE CONTROL

MAURICE B. AUFDERHEIDE
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DATA CORPORATION
DAYTON, OHIO

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AERONAUTICAL SYSTEMS DIVISION

NOTICES

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RECONNAISSANCE SYSTEMS DIVISION
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FOREWORD

This report was orginated by Data Corporation (formerly Systems Development Corporation), Dayton, Ohio under U. S. Air Force Contract AF33(600)-36195, Call No. 2. This contract was initiated and administered by the Data Processing Section, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. Mr. Clifford B. Krumm, Chief of the Data Processing Section and Mr. Frank L. Palazzo, Project Engineer, directed and administered the final work on this project.

Special credit is due Mr. Fred A. Farinet, Photo Electronics and Analysis Section, Reconnaissance Laboratory, Aeronautical Systems Division, as the original Air Force Project Engineer on this project. Mr. Farinet supplied information and data to the authors during their work which saved many man-hours of research and testing.

Acknowledgment is also made of the assistance of Mr. James R. Madden, Head, Test and Evaluation Department of Data Corporation along with other personnel necessary in the preparation of this report.

ABSTRACT

This report incorporates the results of theoretical and laboratory studies in the field of automatic exposure control into a document intended for use by the designer of such systems. The automatic exposure equation is developed upon the basis of photometric analysis and each term is examined analytically. Methods are presented for the analysis of film and sensor characteristics and guidelines for the design and evaluation of automatic exposure controls are given. In addition, the results of laboratory analysis of some controls are reported as well as some significant features of an advanced design. During this program, a laboratory light source for the analysis of automatic exposure controls was developed and a description of this device is included. The Appendix contains a brief bibliography and list of applicable standards and specifications.

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LIST OF SYMBOLS

The following principal symbols are used and are presented in the approximate order in which they appear in the text:

Symbol	Quantity
F	Flux, lumens
I	Intensity, lumens/solid angle
B	Brightness, lumens/solid/angle/unit area
$\mathcal{E}$	Illumination, lumens/unit area
ω	Solid angle, steradians
dA, dS	Elemental area
r	Distance, radial
θ, ϕ	Angles
λ	Wave Length
T	Temperature, usually in degrees Kelvin
K	Symbol signifying the Kelvin temperature scale
W	Power, watts
ϵ	Base of Napierian logarithms
D	Optical density
E	Exposure, usually meter-candle seconds
i	Inertia of emulsion
γ	Gamma, the slope of the D log E curve in the linear range
L	Latitude of an emulsion

E_o	A reference exposure
S_a	Film speed, general
S_w	Weston film speed
t	Time, usually seconds
q	Focal length of lens
f	Aperture number
T	Lens system coefficient. Includes loss and effect of off-axis light gathering depreciation
C	Ratio of film exposure to photoelectric cell output for same light conditions
α	Normalized values of "C"
K	Constant in automatic exposure equation
K_o	Arbitrary constant multiplier portion of "K"
$t_{e.o}$	Effective shutter open time
t_{to}	Total shutter open time
Δ	Used to signify an incremental fractional variation in a parameter, e.g., Δt

CHAPTER I

INTRODUCTION

The design of automatic exposure control systems requires the integration of two dissimilar skills. The formulation of the controlling parameters is based upon the techniques of photometry and the art of reducing brightness levels to a photographic reproduction. While the reduction of these parameters to a working system is within the field of electromechanical design, often the servo designer is familiar with only the electromechanical aspects of the problem and each system design may be subject to an initial study phase to determine the photographic parameters involved. The primary purpose of this report is to assemble in one document the results of both theoretical and laboratory investigations so that this material will be available and useful to the designer of such systems. An attempt has been made to present the information in such a manner that the resulting data is useful in the design of automatic exposure controls for any application. The primary emphasis is on the servo type of control due to its wide applicability to the engineering uses of photography. These systems are characterized by their accuracy, ruggedness, flexibility and wide operating ranges. In many military and engineering applications, the operating environment is such that a mechanically strong closed loop type of system is an absolute necessity.

Automatic exposure control yields greatest benefit to the user in situations where some or all of the following conditions exist:

1. The necessity for manual setting of apertures based on judgement regarding conditions likely to exist in the future.

2. The probability of changes in brightness levels during periods of enforced unattended operation.

3. The possibility of erroneous aperture settings or changes in setting by inexperienced or unauthorized personnel.

4. Changes in lighting during photographic sequences which would require continuous control of aperture setting for optimum results.

5. Completely remote operation of cameras in cases where the number of command and data channels available is limited or where the number of such channels must be minimized.

In such cases, the use of properly designed automatic exposure controls reduces the probability of loss of data due to over or under exposure and provides more assurance of obtaining critical information. In some cases, particularly those involving such occasions as aircraft or missile operations,

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there will be no opportunity to repeat the photographic sequence in case of lost data. In any case, retakes involve expense and lost effort. The advantages of incorporating such equipment into camera systems are evidenced by the increasing application of the principle to commercial and amateur as well as to engineering and military use.

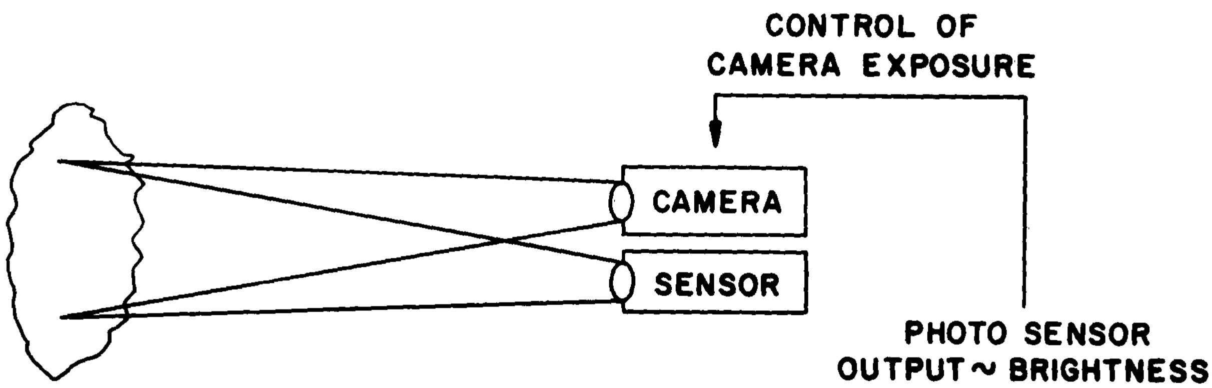
Some of the essential requirements are self-evident immediately upon review of the problem. They are:

1. The system must be as small as possible - no larger than the camera.

2. Since a system will be required for each camera, the cost of the system must be a minimum, by all means less than the camera.

3. It must be simple, rugged, and reliable.

Referring to Figure 1 below, it can be seen that the fundamental problem is that the photosensor of the control system must observe the area viewed by the camera and produce an output proportional to the desired exposure.



AUTOMATIC EXPOSURE CONTROL

FIGURE 1

The system must react proportionally to the sensor observation, since the film should be exposed obeying the well known exposure equation

$$f^2 = KBtS_a \tag{1}$$

The general derivation of this formula is presented in Chapter II of this report.

The following chapter is devoted to the basic physics of light and photometry as applied to the automatic exposure equation in order to introduce the reader to the basic concepts of light measurements and units and definitions employed throughout this report. Later the automatic exposure equation is discussed in detail, and Chapter V discusses the crosscorrelation of the film and sensor characteristics. The results of laboratory evaluation of some automatic exposure controls are reported in Chapter VII.

In the final portion of the Report, some discussion of the principles of calibration and evaluation of automatic exposure controls is presented, together with a bibliography and a collection of useful reference data. It should be recognized by the reader that the primary purpose of the Report is that of assistance to the designer. To this end, simplifying assumptions are often made and empirical standards sometimes employed. This latter situation is especially necessary in cases where specialized information, although it would be extremely useful to the designer, might not be generally available.

CHAPTER II

AUTOMATIC EXPOSURE EQUATION DERIVATION

Prior to continuation, it is desirable that the development and origin of the exposure equation $f^2 = KBtS_a$ be investigated since this will reveal any limitations and restrictions that were incorporated during its development.

Let us first consider the basic operation of the camera. Figure 2 is a simplified illustration of an object being photographed. The operation is as follows:

> The light rays striking the object are reflected by the object toward the camera lens. Upon entering the lens these light rays are directed on the film. The film, having several layers of silver halide coating on its surface, when subjected to light undergoes a photochemical reaction which after development results in black deposits of metallic silver.

The quantity of silver deposited is a function of illumination and time of exposure. The mathematical representation being

$$E = \mathcal{E} t \qquad (2)$$

where:

t - time of exposure in seconds

$\mathcal{E}$ - illumination of the surface usually expressed in meter-candles

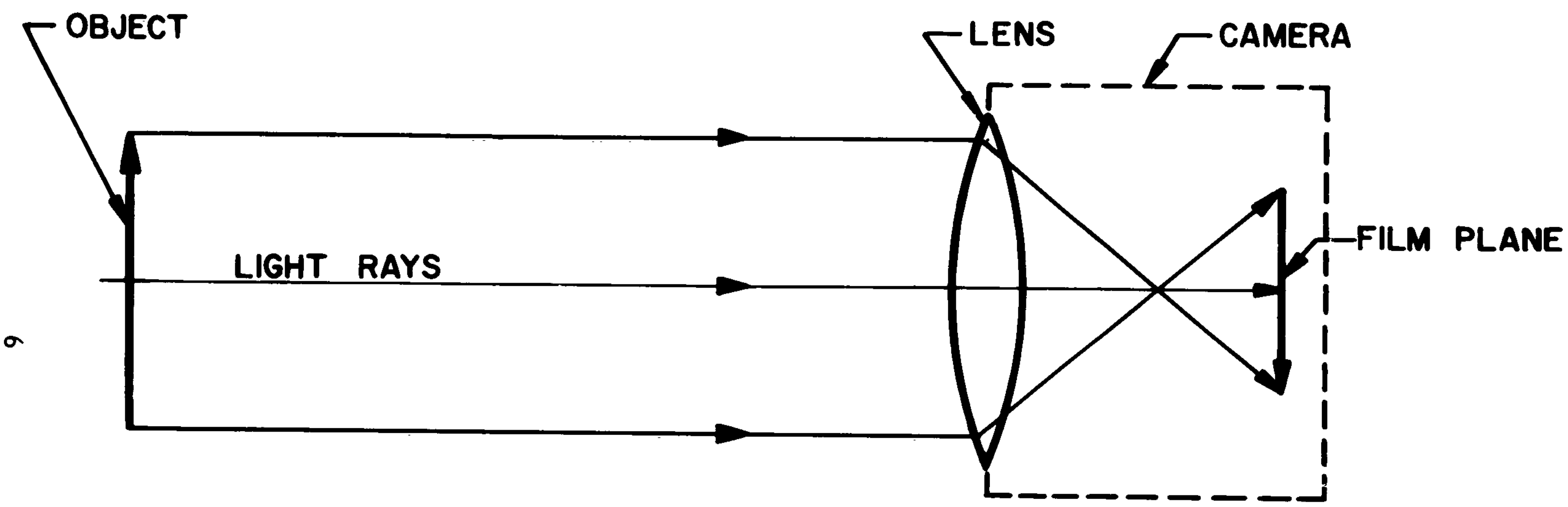
E - unit of photographic exposure usually expressed in meter-candle-seconds

Eq. (2) is sometimes referred to as the reciprocity law of Bunsen and Roscoe.

At present we will confine ourselves with the region in which photographic materials obey the reciprocity law.

Examination of Figure 2 and the reciprocity law reveal that the following factors will affect the exposure of a negative. They are:

1. The lens characteristics
2. Time of exposure
3. Type of photographic material



PHOTOGRAPHIC OPTICAL RELATIONSHIPS
FIGURE 2

Before any mathematical formula relating the exposure and the preceding factors can be obtained, it is necessary that the lens characteristics be investigated. The lens characteristics that are of prime importance are the light transmission factor and the variation of the illumination with respect to the lens f/stop rating.

Figure 3 shows the optical action of a lens with the object placed at a finite distance "d_o" in front of the lens, the diameter of the lens being "D" and the image being formed at a finite distance "d_i" in back of the lens. We are now faced with the problem of determining the relationship between the object brightness and the brightness of the image formed by the lens on the film plane in terms of the object distance, image distance, and diameter of the lens.

Figure 4 illustrates that the brightness of the image is a function of the diameter of the lens. Notice that as the lens diameter is made larger, more of the light rays from point "p" are collected by the lens and projected on the image.

To use the information, it is necessary to determine the mathematical expression relating the image brightness and the object brightness. For the purpose of simplification let us determine the light flux on the front surface of the lens due to point "Q" (See Figure 5). Using the basic laws of photometry,

$$dF_o = B_o \frac{dS\,dA}{r^2} \cos\phi \cos\theta \qquad (3)$$

where:

dF_o - element of flux on the front surface of the lens

B_o - light intensity of the light rays emanating from the object

r - distance from object to lens

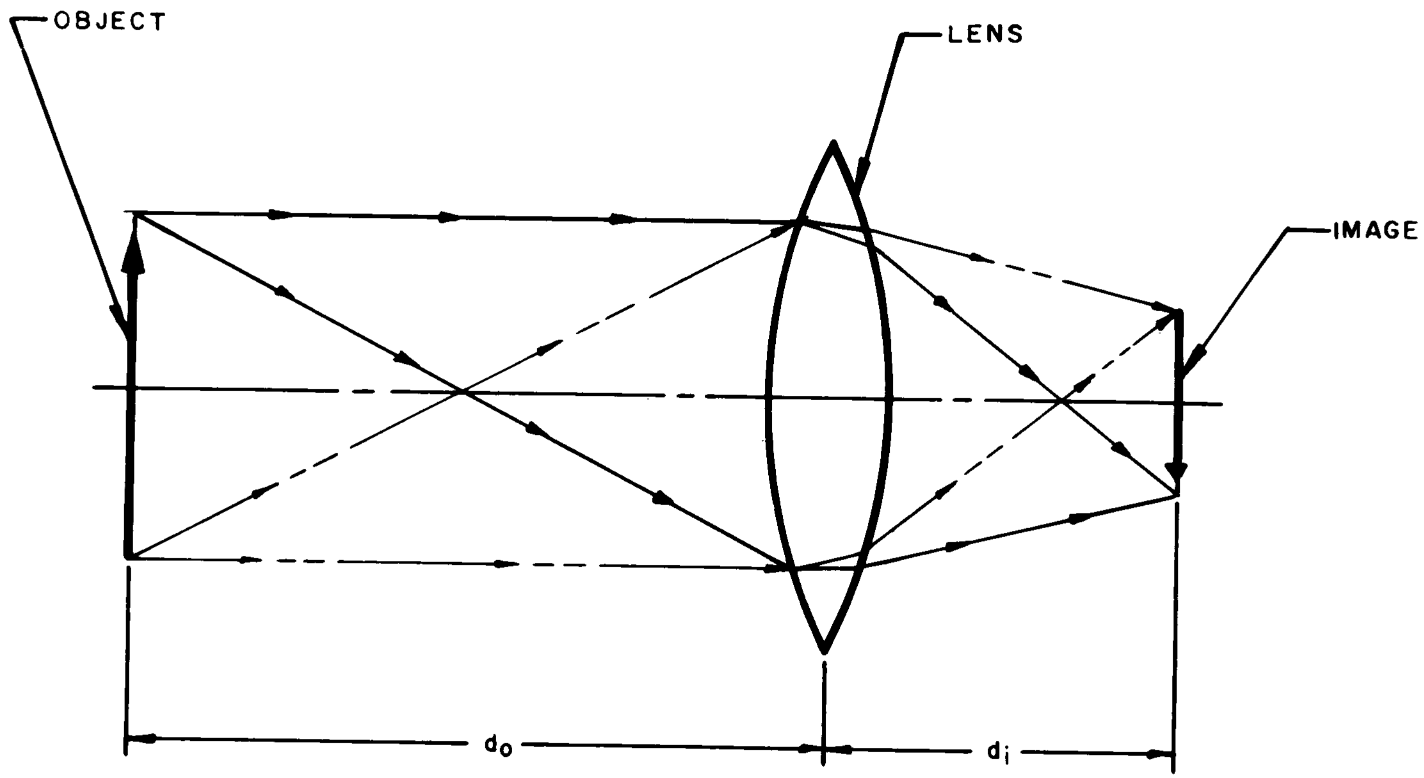
dS - element of area (Q of Figure 5) of the object

dA - element of area of the image

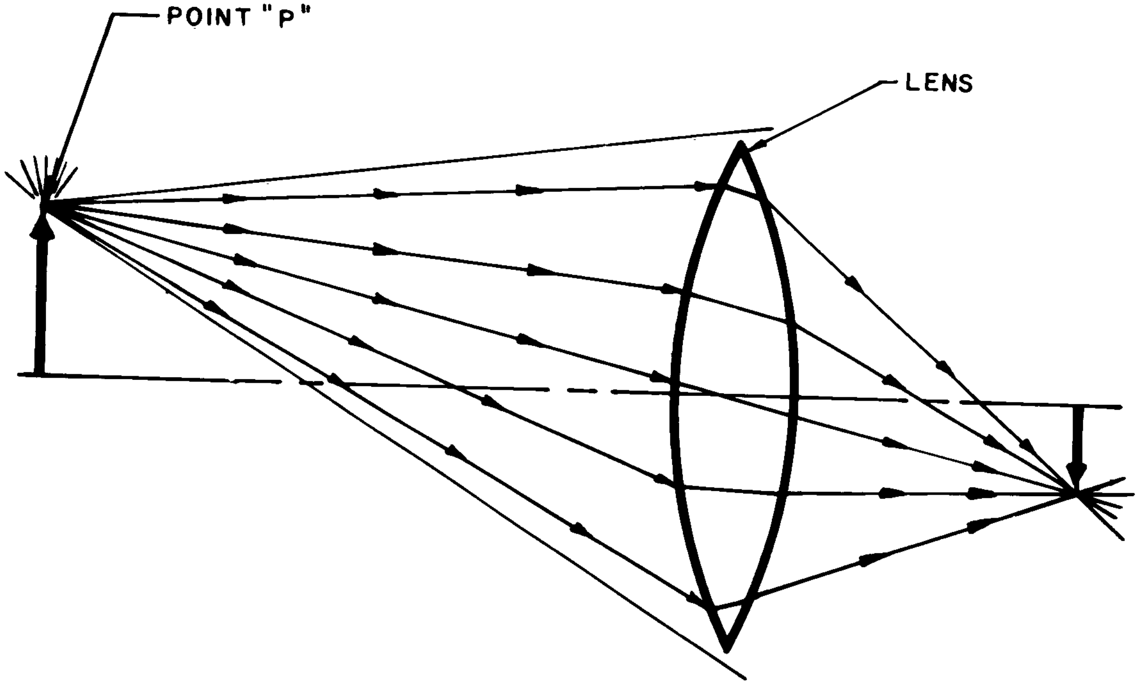
ϕ - angle between optical axis and perpendicular to the plane of the object

θ angle between optical axis and plane perpendicular to plane of image

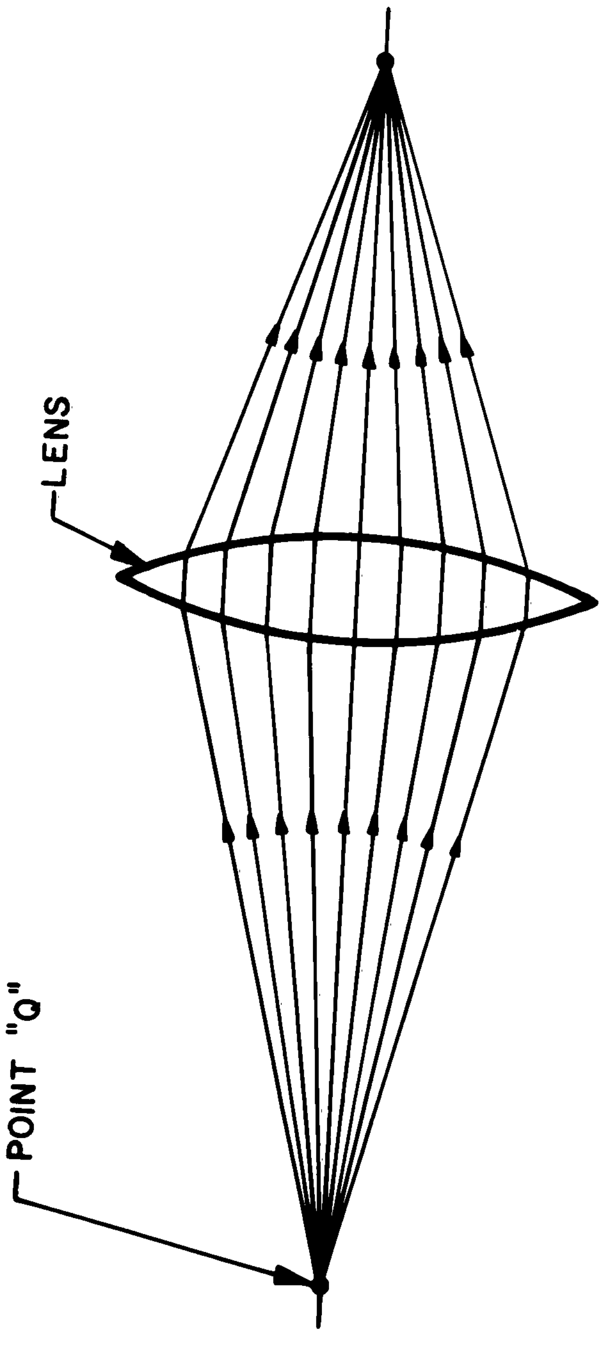
Since the lens has some absorption and losses and there is some nonuniformity in light gathering, let "T" be the effect of interposition of the lens ($T < 1$).



IMAGING PROCESS OF A LENS
FIGURE 3



OBJECT AND IMAGE BRIGHTNESS RELATIONSHIP
FIGURE 4



LIGHT FLUX AT LENS
FIGURE 5

The flux emanating from the image side of the lens due to point "Q" is then given by:

$$dF_i = T(dF_o) \tag{4}$$

where:

dF_i - Flux on the image side of the lens

dF_o - Flux on the object side of the lens

T - Transmission factor of the lens

Now returning to Eq (3) and remembering that "B"

$$dF_o = B_o \left[\frac{dS\,dA}{r^2} \cos\phi \cos\theta\right] \tag{5}$$

is a constant for a given condition, the pencil of light rays are characterized by the bracketed part of Eq. (5) and

$$\frac{dF_o}{B_o} = \frac{dS\,dA}{r^2} \cos\phi \cos\theta \tag{6}$$

therefore

$$\frac{dF_o}{B_o} = \frac{dF_i}{B_i} \tag{7}$$

where:

dF_o - the flux on object side of lens

B_o - brightness of the object, normally candles per unit area

dF_i - flux emanating from image side of lens

B_i - brightness of the image, normally candles per unit area

Substituting Eq. (4) into Eq. (7) and simplifying

$$\frac{dF_o}{B_o} = \frac{T\,dF_o}{B_i} \tag{8}$$

$$B_i = T(B_o) \tag{8a}$$

Eq. (8a) states the important fact that the brightness of the image is a direct function of the object brightness and the lens transmission factor. The photographic process responds to the total amount of energy incident on its surface. This means that the exposure of the film, due to the image formed on it, is a function of the illuminance (by definition flux per unit area). It is now necessary to determine the illuminance of the image from the brightness of the image. (Brightness by definition is the flux per solid angle per unit area). By definition, the illuminance of the image is the product of the unit area brightness of the image and the solid angle formed by the lens and the image distance.

The solid angle formed by the image and the lens in terms of the image distance and the lens diameter is given by Eq. (9):

$$\omega = \frac{\text{AREA}}{(\text{RADIUS})^2} = \frac{\frac{\pi}{4} D_o}{(d_i)^2} = \frac{\pi}{4}\left(\frac{D_o}{d_i}\right)^2 \tag{9}$$

where:

d_i - image distance from lens

D_o - lens diameter

The illuminance of the image is the product of the solid angle and the brightness of the image. In mathematical representation

$$\mathcal{E} = B\,\omega \tag{10}$$

where:

$\mathcal{E}$ - illuminance

ω - solid angle

Substituting Eq. (9) and (8a) into Eq. (10), we have

$$\mathcal{E} = B_o T\left(\frac{\pi}{4}\right)\left(\frac{D_o}{d_i}\right) = \frac{\pi}{4} B_o T\left(\frac{D_o}{d_i}\right)^2 \tag{11}$$

where:

$\mathcal{E}$ - illuminance (flux/unit area)

B_o - brightness of object (candles/unit area)

T - lens transmission factor

D_o - usable lens diameter

d_i - image distance

The focal length "q" of a lens is given by

$$\frac{1}{q} = \frac{1}{d_o} + \frac{1}{d_i} \quad \text{OR} \quad q = \frac{d_o\, d_i}{d_o + d_i} \tag{12}$$

where:

q - focal length of lens

d_i - image distance

d_o - object distance

Since "d_o" is very large compared to "d_i", the case of infinity focus, Eq. (12) reduces to

$$\lim_{d_o \to \infty} \left(\frac{d_o\, d_i}{d_o + d_i} \right) \longrightarrow d_i \tag{13}$$

For infinity focus

$$q \equiv d_i \tag{14}$$

Eq. (11) can now be expressed in terms of the aperture number rather than the lens diameter and image distance using the results of Eq. (14)

$$f = \frac{\text{FOCAL LENGTH}}{\text{LENS DIAMETER}} = \frac{q}{D_o} \tag{15}$$

where:

q - focal length

D_o - lens diameter

f - aperture number

For infinity focus

$$f \equiv \frac{d_i}{D_o} \tag{16}$$

Substituting f for d_i/D_o in Eq. (11), we have

$$\varepsilon = \frac{\pi}{4} B T \frac{1}{f^2} \tag{17}$$

Eq. (17) gives the mathematical relationship between the light transmitted on the film plane and the object brightness in terms of the aperture setting and lens transmission factor.

The exposure of the photosensitive material can be expressed as a function of the following parameters. They are:

1. The scene or object brightness
2. f/stop rating of lens
3. Transmission of the lens
4. Time of exposure
5. Type of photosensitive material

Eq. (17) accounts for factors 1, 2, and 3. When $\mathcal{E}$ is substituted into the following expression

$$E = \mathcal{E} t \tag{18}$$

then

$$E = \frac{\pi}{4} B t T \frac{1}{f^2} \tag{19}$$

Since our prime interest is maintenance of the same exposure "E" when varying the other parameters, we can rearrange the equation so that "E" and other constants are on the left side of the equation, we have

$$\frac{4}{\pi} E = \frac{BTt}{f^2} \tag{20}$$

Since "E" is to remain constant, let $\frac{4}{\pi}\ \frac{E}{T}$ be equal to a constant such that

$$\frac{4}{\pi}\ \frac{E}{T} = \frac{1}{K} \quad \text{OR} \quad K = \frac{\pi T}{4E} \tag{21}$$

Equation (20) will reduce to the following form when Eq. 21 is substituted into Eq. (20) and the reference exposure is expressed in terms of film speed rating:

$$f^2 = K B t S_a \tag{22}$$

In summing up our efforts, it can be said that two restrictions were used in the derivation of the automatic exposure equation, Eq. (22). They are

1. The exposure must obey the reciprocity law

2. The system is operated at infinity focus

These two assumptions may now be examined in respect to their effect on our fundamental objective. It is well known that photosensitive emulsions exhibit some degree of departure from reciprocity law observance in that the actual density obtained under a given set of circumstances is a function of the actual values of time and intensity rather than a function of the product alone. Fortunately the greatest tendency toward reciprocity failure occurs under two sets of conditions which usually fall outside the range of greatest usefulness of automatic exposure control. These two conditions are defined by extreme in either intensity or exposure time for some particular time - intensity product. In these cases, a reasonably designed automatic exposure control would reach the fully open or fully closed position and automatic operation would cease until a sufficiently great light change occurred in the opposite sense. For most purposes, and especially so in view of the observed variation in emulsion characteristics, the assumption of compliance with the reciprocity law is valid and accurate. The second assumption is adopted for convenience in the derivation, since in nearly all applications where automatic exposure control is useful, the camera is operated at infinity focus. Nothing is to be gained in the present work by a more general analysis.

In the following sections, the automatic exposure equation will be subjected to a detailed analysis. In any application of Eq. (15), it should be noted that for a given situation the object brightness B is the independent variable and that an exposure control system is designed to provide automatic adjustment of the aperture number to maintain energy flow to the film constant as B varies. Inasmuch as variations in B occur over the scene as viewed by the lens, it is desirable that the selection of K (and therefore of exposure) be made such that the total range of scene brightness is applied to the dynamic range of the film in such a manner that best use is made of the linear range of the emulsion. In ordinary circumstances the film dynamic range may greatly exceed the range of scene brightness and it follows logically that for reasonable constancy of emulsion characteristics the quantity K of Eq. (22) can be taken as a constant for a given set of operating parameters.

CHAPTER III

THE BASIC PHYSICS OF LIGHT AND PHOTOMETRY AS APPLIED TO THE AUTOMATIC EXPOSURE EQUATION

Section 1. Monochromatic Light

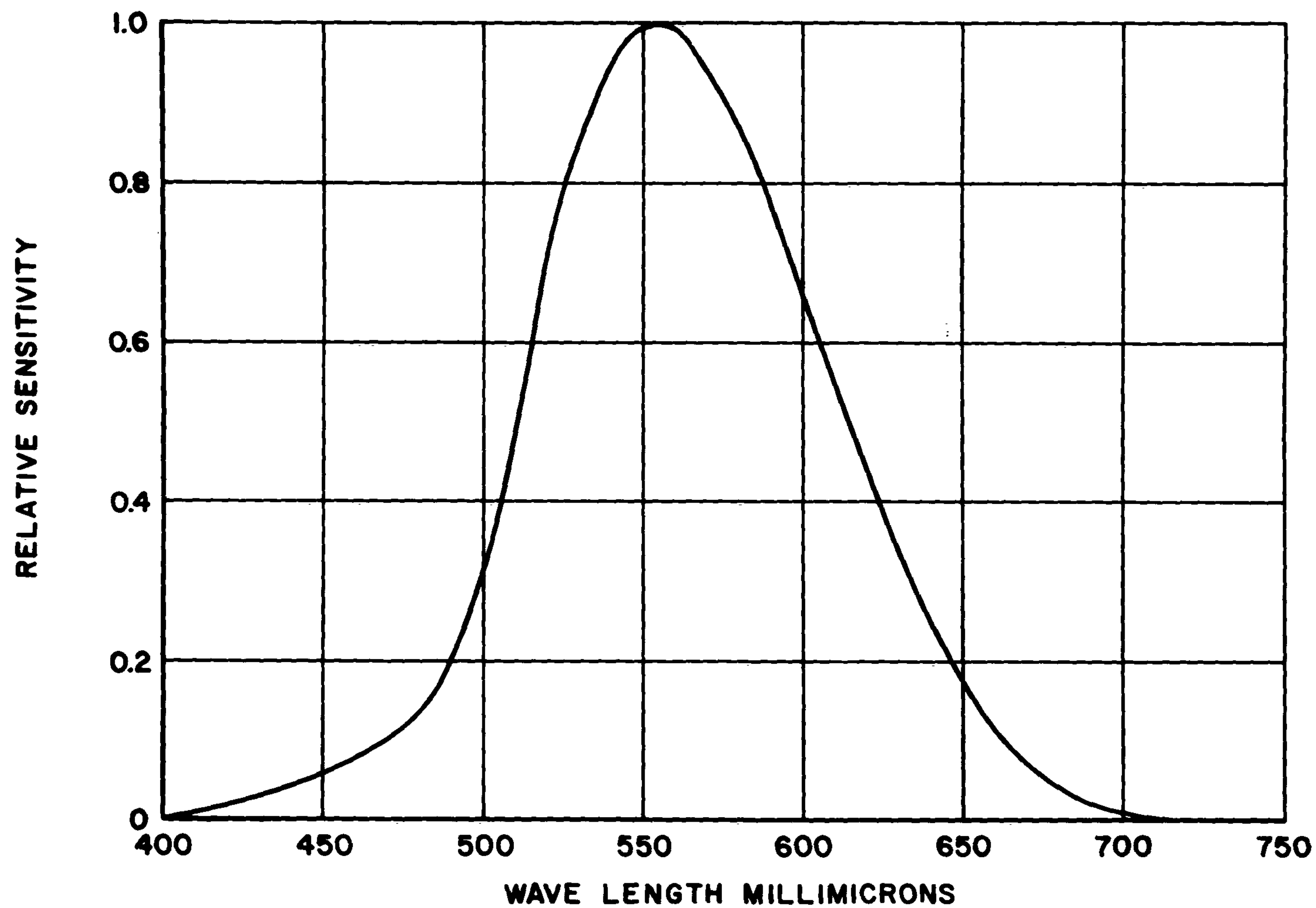
The techniques of photometry have been developed primarily through the effort of the illuminating engineer. Therefore, the choice of the units and concepts have been "tailormade" for applications in the measurements of light distribution (such as room illumination) rather than to systematize the subject of photometry. As a result of this, extreme difficulty is encountered in visualizing the concepts of the basic units and converting the various basic units to equivalent units.

There are only four fundamental photometric qualities. These basic qualities are shown in the table below.

QUALITY	SYMBOL	DIMENSION
Flux	F	Lumen
Intensity	I	Lumens Per Solid Angle
Brightness	B	Lumens Per Solid Angle Per Unit Area
Illumination	ε	Lumens Per Unit Area

Since these four basic photometric qualities are geometrically related, only one of these qualities is to be considered as an independent entity. One would normally be inclined to use the flux as an independent entity; however, due to the ease of measurement of the intensity, the intensity is the standard or independent quality.

Just as current is considered as the flow of electricity, light may be considered as the flow or flux of radiant energy. The unit of light flux is the lumen. Since the eye (as are all photosensitive devices) is frequency selective, it is necessary to define the lumen not only in terms of radiant energy, but also in terms of the frequency at which this energy is being radiated. Figure 6 shows the relative response of the eye over the visible spectrum. If the eye were uniformly sensitive to all wave lengths, then the radiant power expressed in watts would adequately describe the amount of flux. Because of this limitation



SENSITIVITY CURVE OF THE HUMAN EYE

FIGURE 6

of the eye, the lumen is defined in the following manner:

> One lumen is equivalent to 0.00146 watts of monochromatic green light having a wave length of 555 millimicrons. Or, that 1 watt of green light having a wave length of 555 millimicrons contains 685 lumens.

The lumen obviously has the dimension of power. Stating this mathematically, we have

$$L = V K_v W \tag{23}$$

where:

L - flux in lumens

V - relative response with respect to 555 millimicrons

K_v - lumirous efficiency in lumens/watts

W - power in watts

At present our efforts will be confined to monochromatic light for the development of the remaining photometric quantities. The relationship between the luminous flux, radiant flux and luminous efficiency will then be derived for light in general.

The simplest source of light is a point source of light. The intensity of such a source is given in terms of the flux per unit solid angle.

$$I = \frac{dF}{d\omega} \tag{24}$$

where:

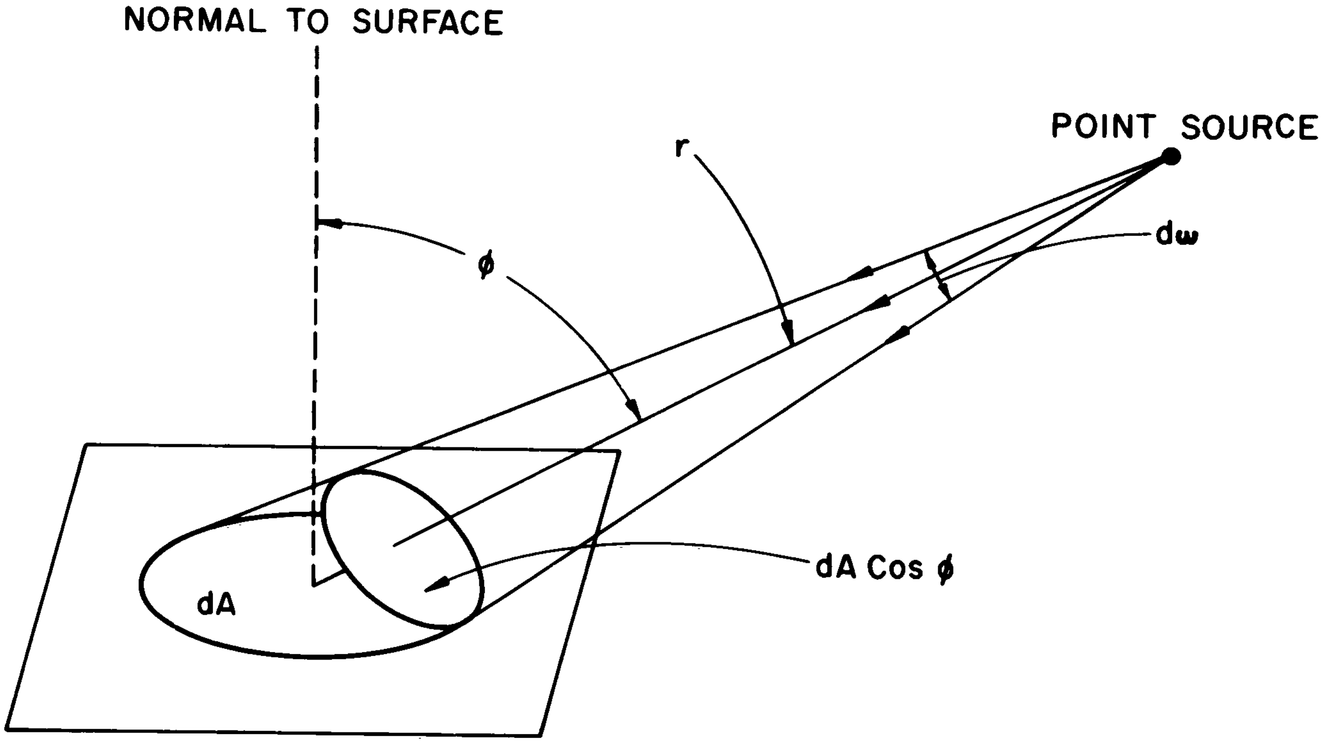
dF - flux in lumens

ω - solid angle in steradians

I - intensity

The unit of intensity is the candle; it is equal to one lumen per steradian.

A steradian by definition is the solid angle subtended at the center of a sphere by an area of arbitrary shape on the surface of the sphere equal to the square of the radius. Therefore, there are 4π steradians in a sphere. A point source having an intensity of one candle in all directions is equivalent to a point source of flux of 4π lumens.



INCIDENT LIGHT FLUX ON A SURFACE
DUE TO A POINT SOURCE EMITTER
FIGURE 7

The light flux incident on a surface due to a point source can be determined with the aid of Figure 7.

$$dF = I \frac{dA \cos\phi}{r^2} \tag{25}$$

where:

dF - element of flux

dA - element of area on the surface

r - distance from source to dA cos

I - intensity of the point source

The total flux can be evaluated by integrating Eq. (25)

$$F = \iint_A I \frac{\cos\phi \, dA}{r^2} \tag{26}$$

Since most light sources encountered are not point sources but extended sources, it is necessary that Eq. (25) and (26) be expressed so that they will be useful in obtaining the flux incident on an area as a result of light source other than a point source.

Using Figure 8, the flux incident on a surface due to an extended light source can be found by the following equation:

$$dF = \frac{B \, dS \, dA}{r^2} \cos\phi \cos\theta \tag{27}$$

where:

B - brightness of the source in candles per unit area

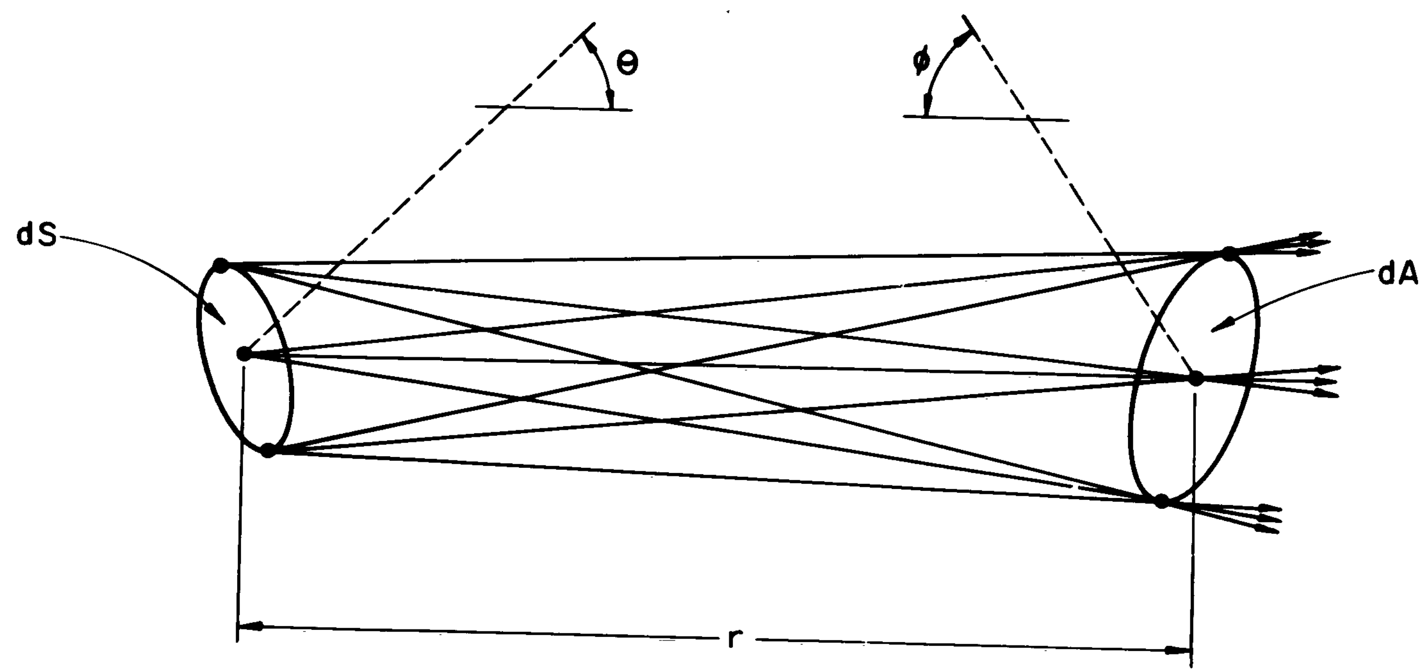
dS - element of area of the source

dA - element of area of the illuminated surface

ϕ - angle that the plane of the illuminated surface makes with the normal to the optical axis

θ - angle that the plane of the source brightness makes with the normal to the optical axis

dF - an element of flux



FLUX DUE TO EXTENDED LIGHT SOURCE
FIGURE 8

Integrating Eq. (27), we have

$$F = \int_A \int_S \frac{B}{r^2} \cos\phi \cos\theta \, dS \, dA \tag{28}$$

When the luminous flux strikes a surface, we say the surface is illuminated. Illumination is defined as the ratio of incident flux per unit area. Expressed in differential form

$$d\mathcal{E} = \frac{dF}{dA} \tag{29}$$

where:

- dF - element of flux
- dA - element of area
- $d\mathcal{E}$ - element of illuminance

If Eq. (27) is substituted in Eq. (29)

$$d\mathcal{E} = \frac{B \, dS}{r^2} \cos\phi \cos\theta \tag{30}$$

Eq. (30) makes it possible to determine the illumination of a surface under the most general conditions. Integrating Eq. (30)

$$\mathcal{E} = \int_S \frac{B}{r^2} \cos\phi \cos\theta \tag{31}$$

It should be noted that when the brightness of an extended source is multiplied by the solid angle subtended by this source the illumination is obtained.

$$B = \frac{\text{CANDLES}}{\text{UNIT AREA}} = \frac{\frac{\text{FLUX}}{\text{SOLID ANGLE}}}{\text{UNIT AREA}} = \frac{\text{FLUX}}{(\text{SOLID ANGLE})(\text{AREA})}$$

Therefore,

$$\mathcal{E} = B\omega = \frac{\text{FLUX}}{(\text{SOLID ANGLE})(\text{UNIT AREA})} \times \text{SOLID ANGLE} = \frac{\text{FLUX}}{\text{UNIT AREA}}$$

The illumination is given by

$$\mathcal{E} = B\omega$$

One unit that has not been expressed so far in this section is the foot-candle. The foot-candle is a unit of brightness. It is equivalent to one candle per square foot. Since the areas may be expressed in either metric or English units, it is necessary to be able to convert from one set of units to another. (see Appendix I)

CHAPTER III

THE BASIC PHYSICS OF LIGHT AND PHOTOMETRY AS APPLIED TO THE AUTOMATIC EXPOSURE EQUATION

Section 2. White Light

A light source is normally specified in terms of its "color temperature". When it is stated that the color temperature of a lamp is 3200° Kelvin, it is understood that the lamp is producing radiation having the same visual characteristics as a blackbody radiator would have if heated to that given temperature.

The energy of a blackbody radiator at any wave length for a given temperature can be determined by Planck's law:

$$W = \frac{C_1 \lambda^{-5}}{\epsilon^{C_2/\lambda T} - 1} \tag{32}$$

where:

W_λ - radiant energy in watts per square centimeter per millimicron wave length

C_1 - 3.703×10^{16} numerical constant for given units

C_2 - 1.433×10^{7} numerical constant for given units

T - Color temperature in Kelvin Temperature Scale

λ - Wave length in millimicrons

Using Eq. (32) the spectral distribution of energy as a function of wave length was determined for blackbody radiators having color temperatures of 3000° K, 5500° K, and 18,000 °K. They are shown in tabular form in Table 1.

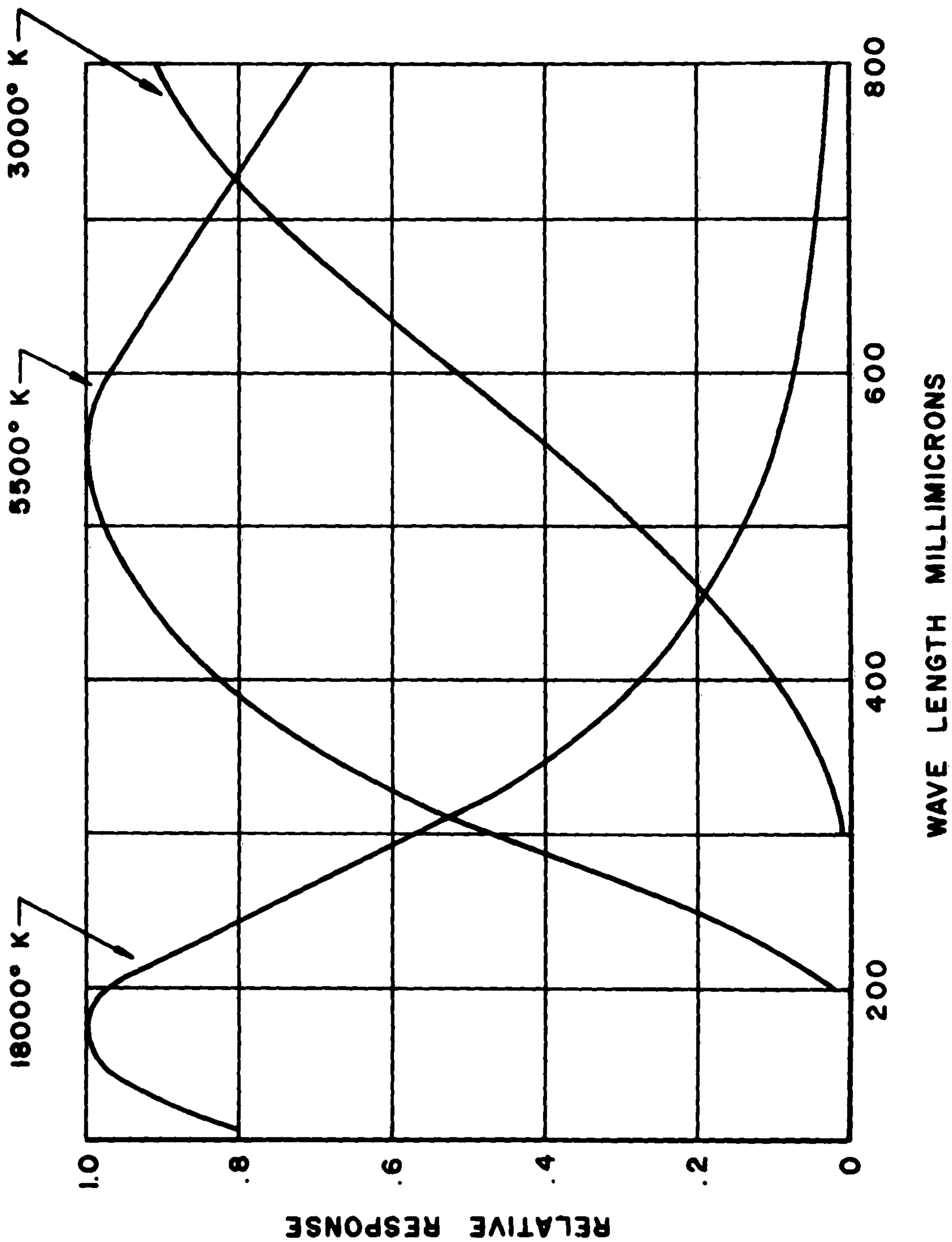
In most applications, it is convenient to work with the energy curves normalized with respect to the maximum point on the curve. Noting that for the range of λ and T, Eq. (32) can be reduced to

$$W_\lambda = \frac{C_1 \lambda^{-5}}{\epsilon^{C_2/\lambda T}} \tag{33}$$

since

$$\epsilon^{C_2/\lambda T} >> 1$$

The wave length of maximum energy, λ_{max}, can be determined approximately by differentiating Eq. (33) and setting it equal to zero. Then solving for λ_{max} in terms of C_2 and T we have



NORMALIZED SPECTRAL DISTRIBUTIONS

FIGURE 9

$$\lambda_{MAX} = \frac{0.2\, C_2}{T} \tag{34}$$

When this was done for the three color temperatures of interest the wave length of maximum energy for each color temperatures was found to be:

3000° Kelvin	λ max	=	956 millimicrons
	W max	=	.315 watts/cm^2
5500° Kelvin	λ max	=	521 millimicrons
	W max	=	6.51 watts/cm^2
$18,000^\circ$ Kelvin	λ max	=	160 millimicrons
	W max	=	2000 watts/cm^2

The normalized curves of energy distribution as function of wave length are shown in Figure 9.

It is of interest to note that the area under the curves of Figure 9 represent the total energy density (relative to energy density at λ max) of the source at each color temperature. This can be verified by the fact that the dimensions of the ordinate axis are watts/unit area per wave length and the dimensions of the abscissa axis are wave lengths.

"Y" Axis Dimensions "X" Axis Dimensions

$$\frac{\text{Watts per unit area}}{\text{Wave Length}} \times \text{Wave Length} = \frac{\text{Watts}}{\text{Unit Area}}$$

TABLE I

SPECTRAL DISTRIBUTION OF BLACKBODY RADIATORS AT VARIOUS COLOR TEMPERATURES

3000° KELVIN BLACKBODY RADIATOR
(APPROXIMATE COLOR TEMPERATURE OF INCANDESCENT LAMPS)

λ MILLIMICRONS	WATTS/cm^2
300	.002
400	.024
500	.085
600	.169
700	.243
800	.292
1000	.317

5500° KELVIN BLACKBODY RADIATOR
(DAYLIGHT)

λ MILLIMICRONS	WATTS/cm^2
200	0.26
400	5.38
500	6.50
550	6.49
600	6.29
700	5.47
800	4.64

18,000° KELVIN BLACKPODY RADIATOR

λ MILLIMICRONS	WATTS/cm^2
100	1.29×10^4
159	2.00×10^4
200	1.52×10^4
300	1.16×10^4
400	5.72×10^3
500	3.04×10^3
600	1.72×10^3
700	1.03×10^3
800	0.66×10^3

CHAPTER IV

SENSOR AND FILM INTERDEPENDENCY

Section 1. Method of Calculating Film And Photocell Response to White Light

Figure 10 Curve "A" shows the relative radiated spectral distribution of a blackbody at 3000 $^{\circ}$K. It should be observed that the light energy is a continuous band of frequencies where each wave length contributes some portion of the total energy. It was pointed out in the last chapter that the area under the curve represents the total output.

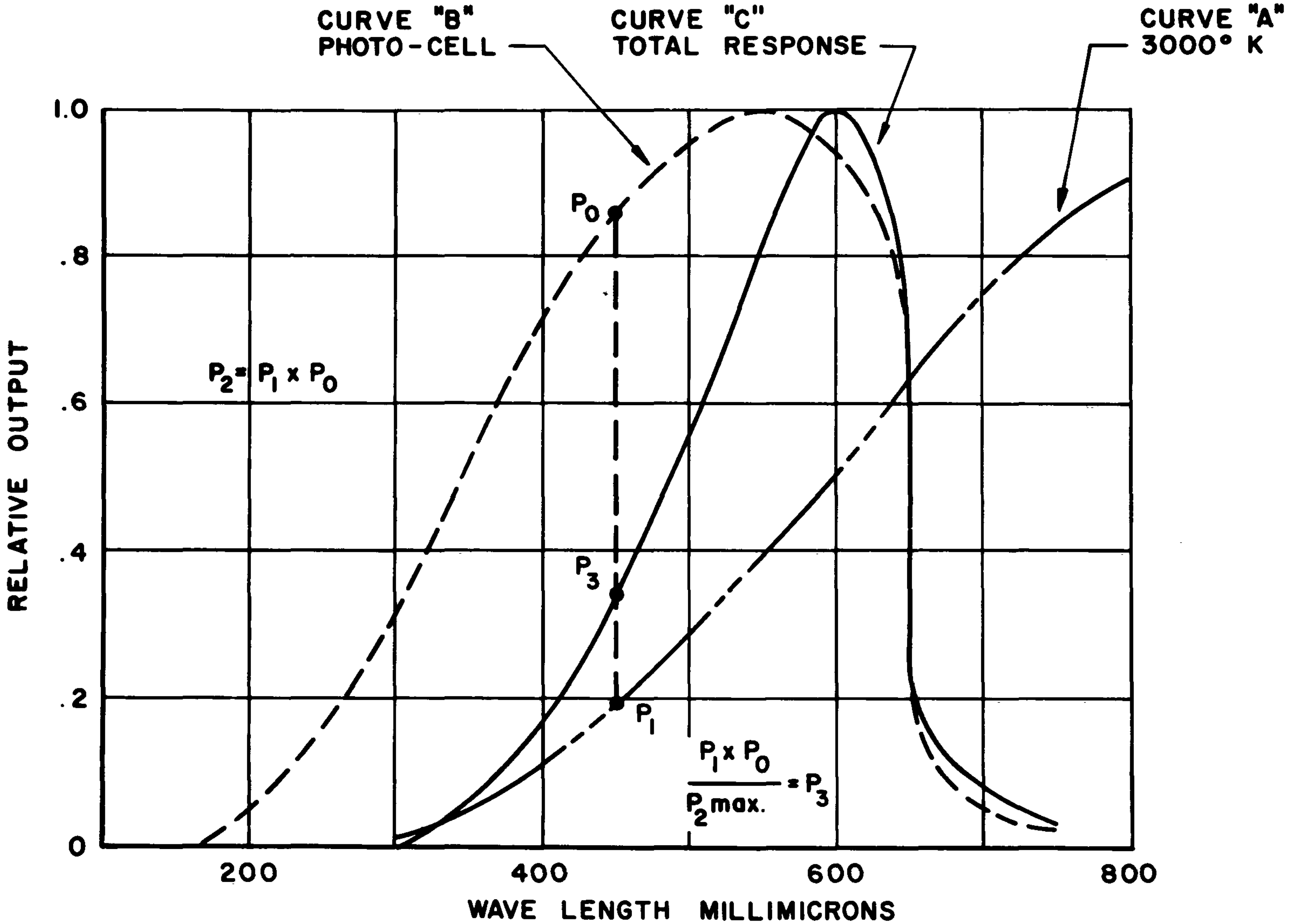
Curve "B" of the same figure is a normalized response curve of a selenium cell. If one wishes to obtain the photocell response to 3000° K, one must apply the following technique since the response of the cell is different at each wave length (the amount of energy contributed at each wave length is also different).

Curve "A" of Figure 10 shows the spectral distribution of the energy of a 3000° K light source, normalized, and the normalized response of a selenium photocell. When the "Y" axis value of Curve "A" is multiplied by the "Y" axis value of Curve "B" at each wave length, then a third curve will be obtained. This is the overall response of the light and photocell combination. As a matter of convenience, the set of values obtained by the multiplication of the two curves is normalized with respect to the maximum point of the curve. This then gives the energy output curve shown in Curve "C" of Figure 10.

The area under this curve represents the total radiant power impressed on the photocell normalized with respect to its maximum value and weight according to the wave length sensitivity of the cell. If the sensitivity of the photocell is known and the area under the curve determined, the output of the photocell can be determined.

Normally the sensitivity of the photocell is given in terms of the output current (or voltage) per microwatt of incident light per unit area of the cell. Once the area under the curve of Figure 10 is determined, the total energy density is obtained by multiplying the area under the Curve "C" by the energy at the maximum point of Curve "C" and photocell sensitivity. Care must be exercised when performing these calculations to insure that they are dimensionally correct. Figure 10 illustrates the procedure outlined above for the data shown in Table 2.

The procedure shown for determining the response of the photocell is also used to determine the response of film to light at a given color temperature. Film sensitivity is normally specified in terms of the number of erg/sec per unit area required to produce a density of 0.1 above base fog.



NORMALIZED SELENIUM CELL RESPONSE TO 3000° KELVIN LIGHT SOURCE

FIGURE 10

TABLE 2

NUMERICAL COMPUTATIONS RELATIVE TO FIGURE 10

Wave Length (Millimicrons)	Relative Light Output ($3000^{o}K$) "P_1"	Relative Response of Photocell "P_o"	$P_1 \times P_o$	Overall Response $\frac{P_1 \times P_o}{P_2 \text{ max}}$
300	0.010	0.315	0.00315	0.006
350	0.050	0.525	0.02620	0.055
400	0.105	0.710	0.07880	0.165
450	0.190	0.865	0.16500	0.346
500	0.280	0.950	0.26600	0.558
550	0.390	1.000	0.39000	0.818
600	0.505	0.945	0.47700	1.000
650	0.630	0.200	0.12600	0.264
700	0.750	0.055	0.04130	0.086
750	0.845	0.02	0.01700	0.035

CHAPTER IV

SENSOR AND FILM INTERDEPENDENCY

Section 2. Calculations of Film And Photocell Response to White Light

As will become increasingly evident, it is highly important that the response of the photosensor to light be matched to that of the film to as high a degree as is feasible. Using the normalized response of Class A film as shown in Figure 11 and by the same general method developed in the preceding Section, one can calculate the response of the film to light of various color temperatures.

Figures 12 through 14 show the resultant response curve of the film to the three given color temperature light sources. Each graph, in the upper left hand corner, gives the wave length of maximum response, λ_{max}, the value of the response λ_{max} designated as TR and the area enclosed by the response curve. The relative exposure of film as a result of the light can be determined using this data in the following equation.

$$E = K_v (A_f)(TR)(S_f)(S_1) \tag{35}$$

where:

E - the exposure per unit time (illuminance)

K_v - energy density of light at λ_{max}

A_f - area enclosed by the resultant curve

TR - Transfer Ratio

S_f - Film sensitivity given in film density per unit power density

S_1 - Constant for the scale factors of graphs

A similar expression can be obtained applying the same technique to the sensor. First, the response of the sensor to light of various color temperatures is determined, resulting in the curves of Figures 15 through 26 for various sensors.

$$V = K_v (A_s)(TR)(S_s)(S_1) \tag{36}$$

where:

V - the electrical signal output of sensors

K_v - energy density of light at λ_{max}

A_s - Area enclosed by the resultant curve of sensor and light

TR - Transfer Ratio

S_s - Sensor sensitivity given in electrical output per unit power density

S_1 - constant for the scale factor of graphs

It should be noted that S_1 remains the same for sensor and film since the same scale factors were used in all graphs.

If Eq. (35) is divided by Eq. (36) then an expression for the exposure of the film as a function of sensor output is obtained.

Dividing, we have

$$\frac{E}{V} = \frac{K_v(A_f)(TR)(S_f)(S_1)}{K_v(A_s)(TR)(S_s)(S_1)} \tag{37}$$

$$E = \frac{(A_f)(TR)(S_f)}{(A_s)(TR)(S_s)} V = CV \tag{38}$$

An ideal system is one in which C of Eq. (38) remains constant. The system then would function properly independent of the color temperature of the light. Since S_f and S_s may be taken as constant, Eq. (38) reduces to

$$C \sim \frac{E}{V} \sim \frac{A_f \; TR}{A_s \; TR} \tag{39}$$

The relative value of C was determined for the three given color temperatures for various photocell coatings. The coatings investigated were:

1. Selenium photocell coating
2. S-4 coating
3. S-12 coating
4. S-15 coating (used in KS-27A System)

Table 3 shows the results of these calculations using Eq. (39) and normalizing the value of C obtained at 5500° K for each film/sensor combination.

Examination of Eq. (39) shows that C is the ratio of the exposure to the unit signal output of the sensor and is equivalent to the signal output of the sensor when the scene brightness produces an exposure E on the film. Since the system is normally evaluated and operated with a light source having a given color temperature at 5500° K, it is the magnitude of the input control signal of the servo for a desired exposure. When the color temperature of the light is varied, the value of C varies as a result of the difference in the spectral response of photocell and film.

If C is normalized with respect to the value of C at 5500° K, then one can approximately determine with exposure of the film as a function of the color temperature of the light source when the exposure is controlled by the photosensor. Using Eq. (18),

$$\frac{\dfrac{E_1}{V_1}}{\dfrac{E_{5500}}{V_{5500}}} = \frac{C_1}{C_{5500}} = \alpha \qquad (40)$$

where:

α - the relative value of C with respect to C at 5500°K

1 - denotes the various parameters at a given color temperature light

5500- denotes the various parameters at 5500° K color temperature light

Since this sensor output signal controls positioning of the aperture for the proper exposure, let us now determine the exposure E at some color temperature other than 5500° K. Using Eq. (40), we now have

$$\frac{\dfrac{E_x}{V_x}}{\dfrac{E_{5500}}{V_{5500}}} = \alpha \quad \text{OR} \quad E_x = \alpha E_{5500} \quad (\text{WHEN } V_1 = V_x) \qquad (41)$$

Eq. (41) gives us the relationship of the exposure in terms of the exposure of the film when the light has a color temperature of 5500°K. The above statement can be clarified by considering a specific condition. Let us consider an exposure control system in which a selenium cell is employed as a sensor. Referring to Table 3, let us consider values of C, α, and $\frac{1}{\alpha}$ for the 3000°, 5500°, and $18,000^\circ$K color temperature light source.

Initially the system is adjusted so that proper exposure is obtained when the sensor and film are subjected to light having a color temperature of 5500°K. When the color temperature drops to 3000°, then the value of α for the sensor is 1.16. This means that the exposure per unit signal output of the sensor has increased. In order to maintain the same exposure, the control signal output of the sensor must be increased by a factor of $\frac{1}{\alpha}$. Since this does not occur, the output of the sensor causes the servo unit to control the aperture as if the brightness were the same value as at 5500°K. The value of α being 1.16 tells us the relative sensitivity of the film is 1.16 times greater at this color temperature and the exposure of the film is 1.16 greater than the desired value. The density of the film will then be approximately .06 greater than the exposure to 5500°K light (noting that the log 1.16 = .06). The same effect occurs when the light source has a color temperature of 18,000 °K. The value of α at this color temperature is 0.65. The servo will position the aperture as if the light were of a color temperature of 5500°K. Since the relative film sensitivity for 18,000° is 0.65, the illumination on the film will be 0.65 the desired exposure value. The density of the film will be about 0.19 less than the desired value of density.

For the color temperature range of 3000° to 18,000° K, the variation in the relative value for each sensor follows:

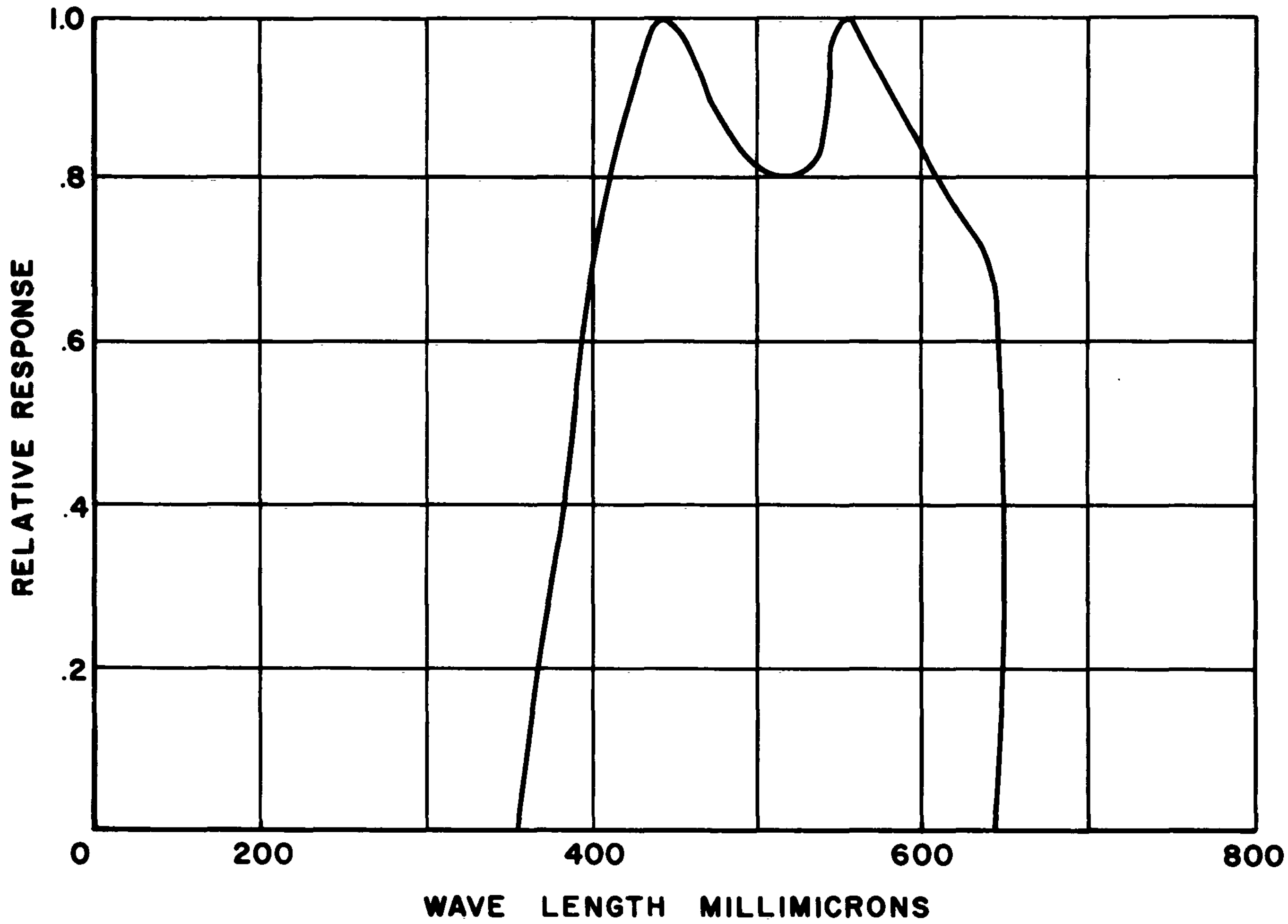
1.	Selenium Cell	1.732
2.	S-4 Coating	3.78
3.	S-12 Coating	1.86
4.	S-15 Coating	1.48

From the above data, it is immediately obvious that the S-15 response is the best in terms of color temperature dependence with the second choice being the selenium cell.

TABLE 3

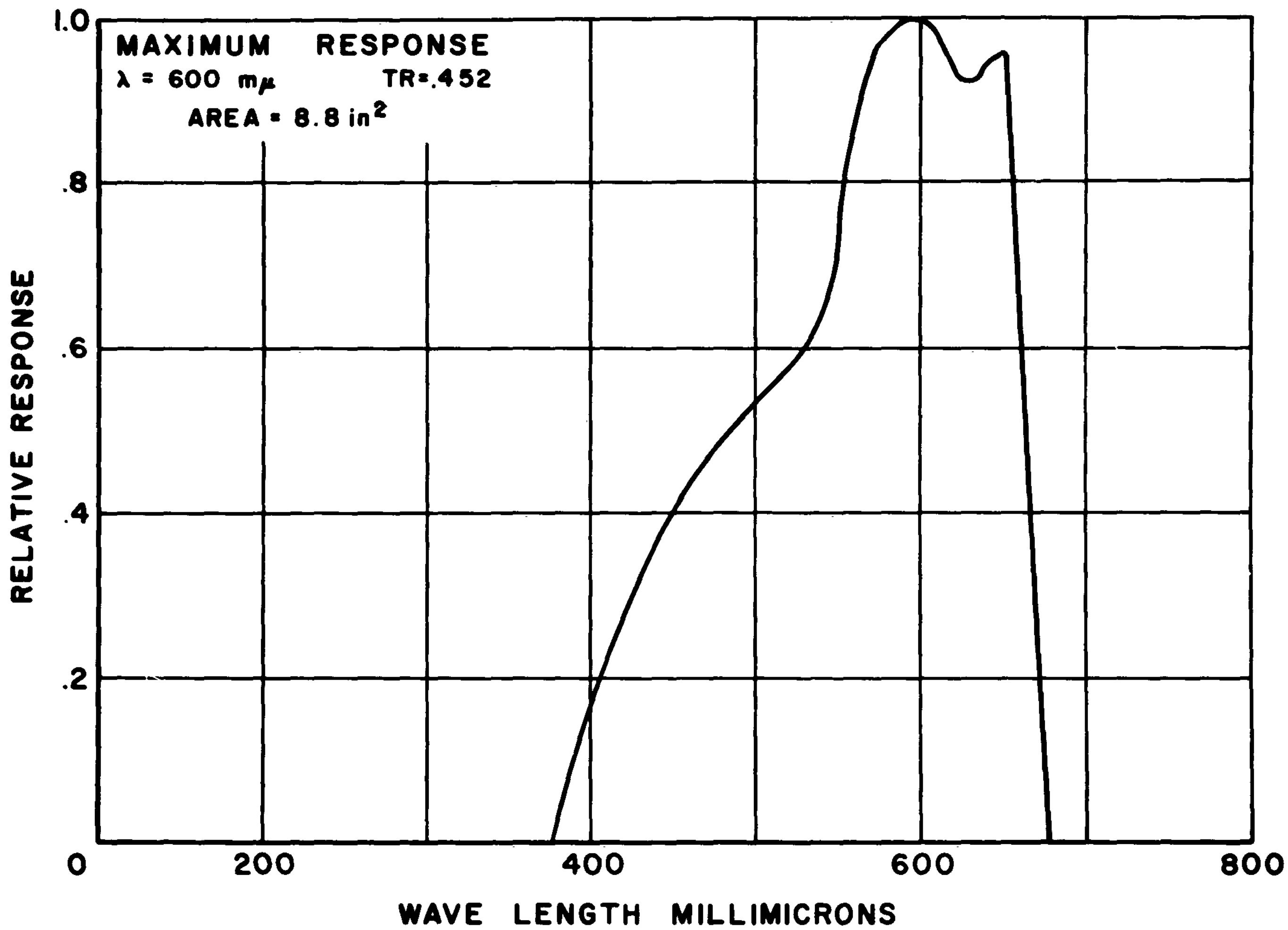
CLASS "A" FILM AND SENSOR CORRELATION DATA

Type of Cell	Color Temp. ($^{\circ}$ K)	C	α	$\frac{1}{\alpha}$
Selenium	3000	0.971	1.158	0.864
	5500	0.838	1.000	1.000
	18000	0.545	0.650	1.538
S-4	3000	2.37	1.958	0.511
	5500	1.21	1.000	1.000
	18000	0.627	0.518	1.931
S-12	3000	8.47	1.448	0.691
	5500	5.85	1.000	1.000
	18000	4.55	0.778	1.286
S-15	3000	0.937	0.786	1.272
	5500	1.192	1.000	1.000
	18000	1.381	1.159	0.863



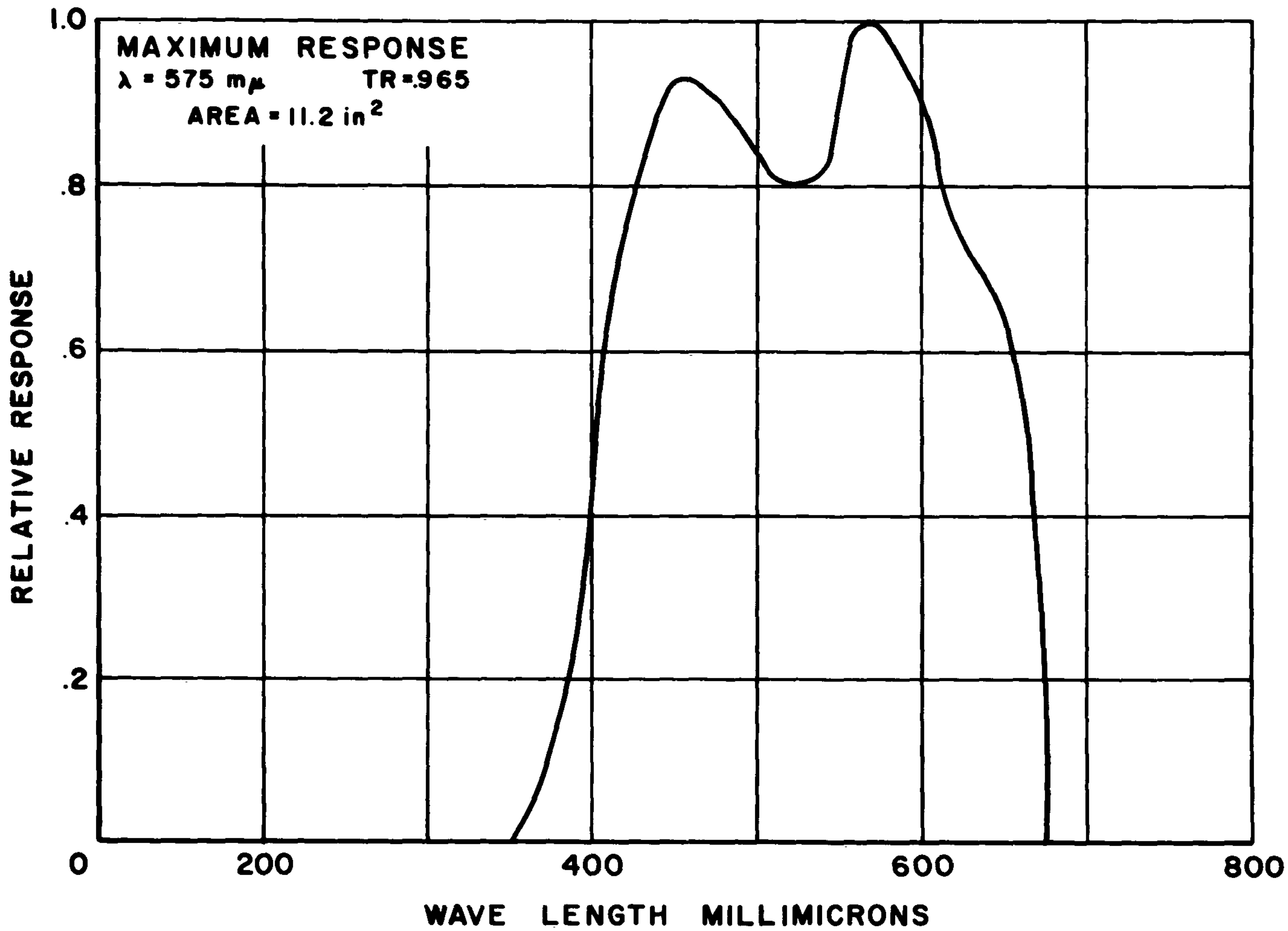
NORMALIZED RESPONSE OF CLASS "A" FILM

FIGURE 11



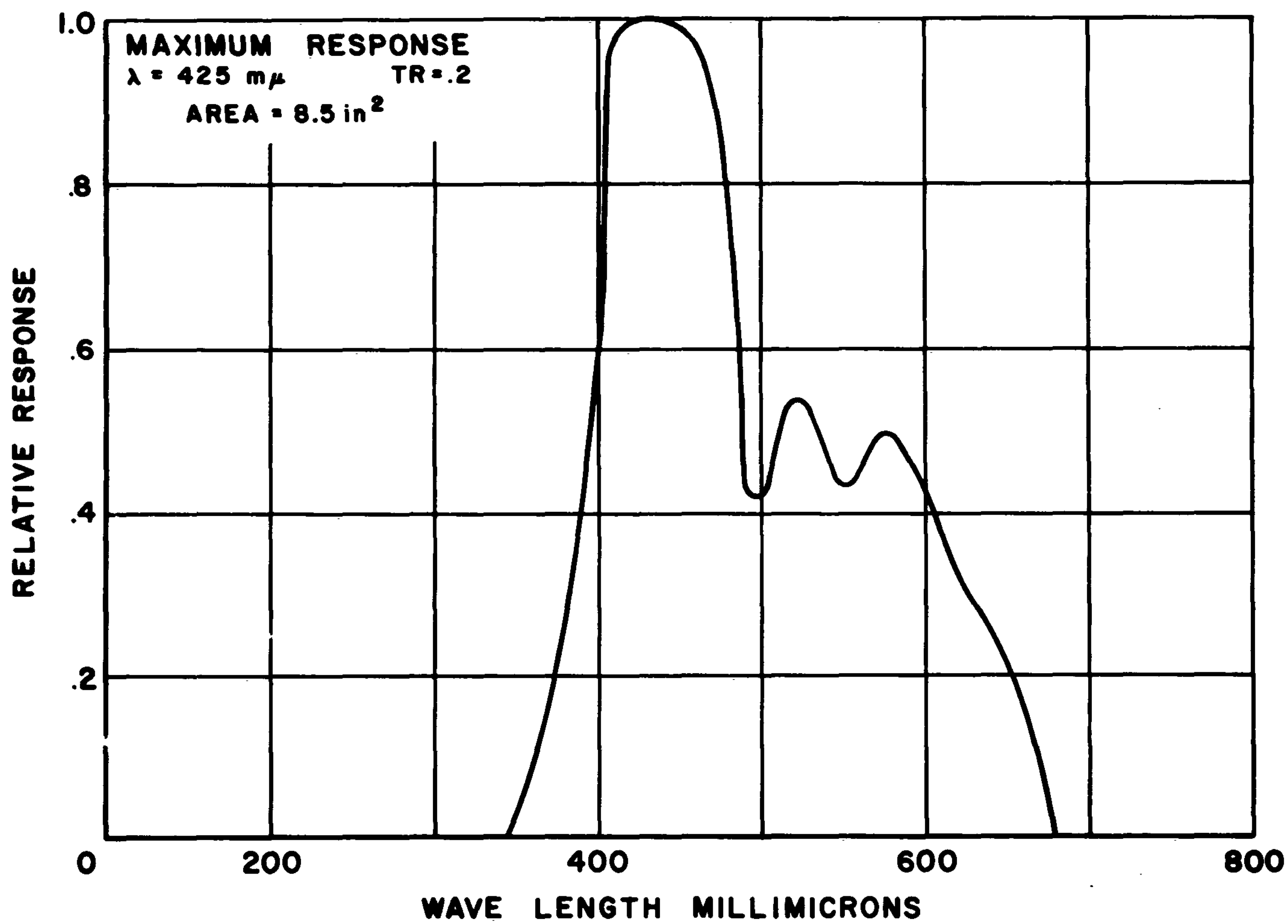
CLASS A FILM RESPONSE
(3000° KELVIN LIGHT SOURCE)

FIGURE 12



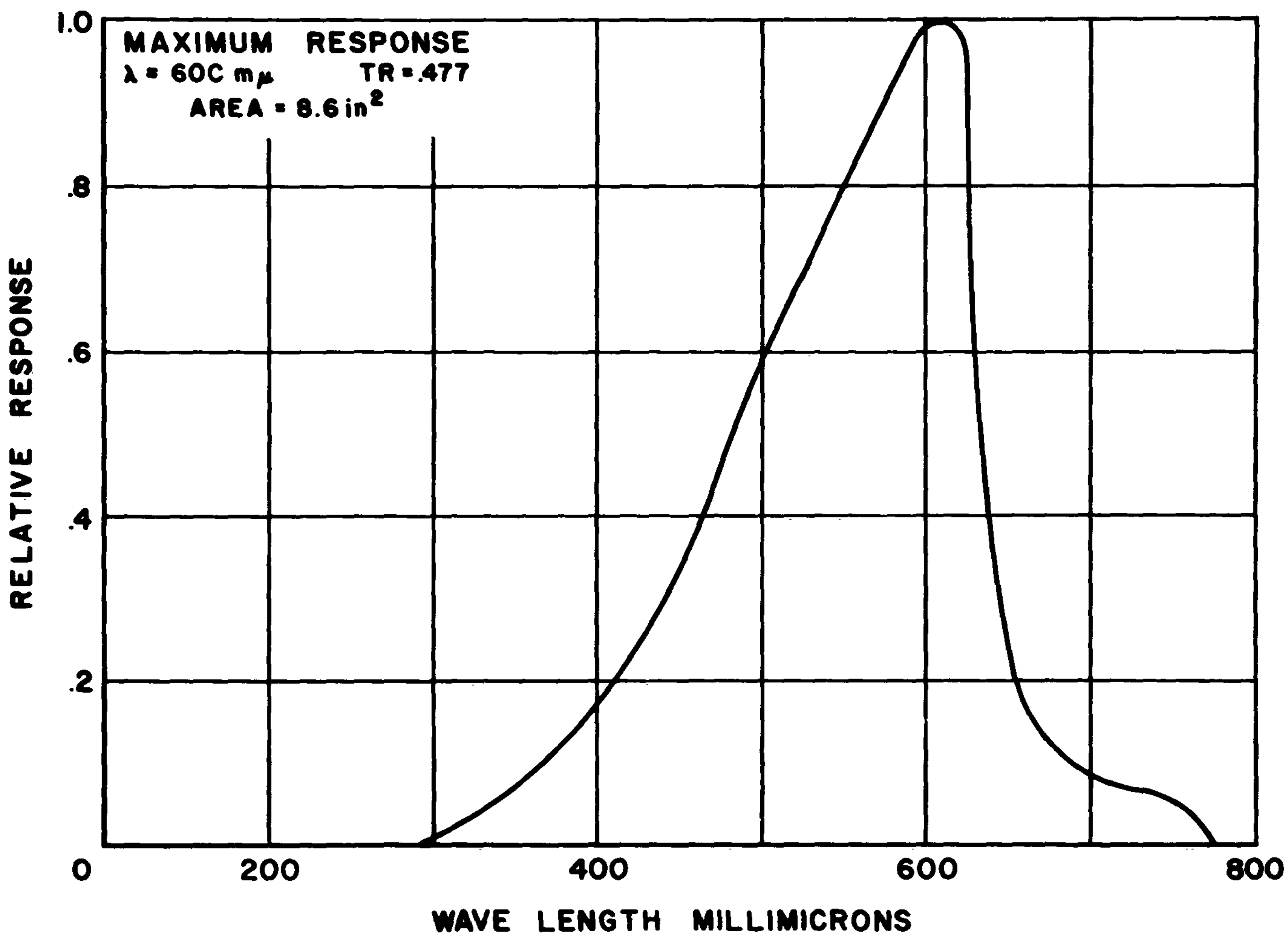
CLASS A FILM RESPONSE
(5500° KELVIN LIGHT SOURCE)

FIGURE 13



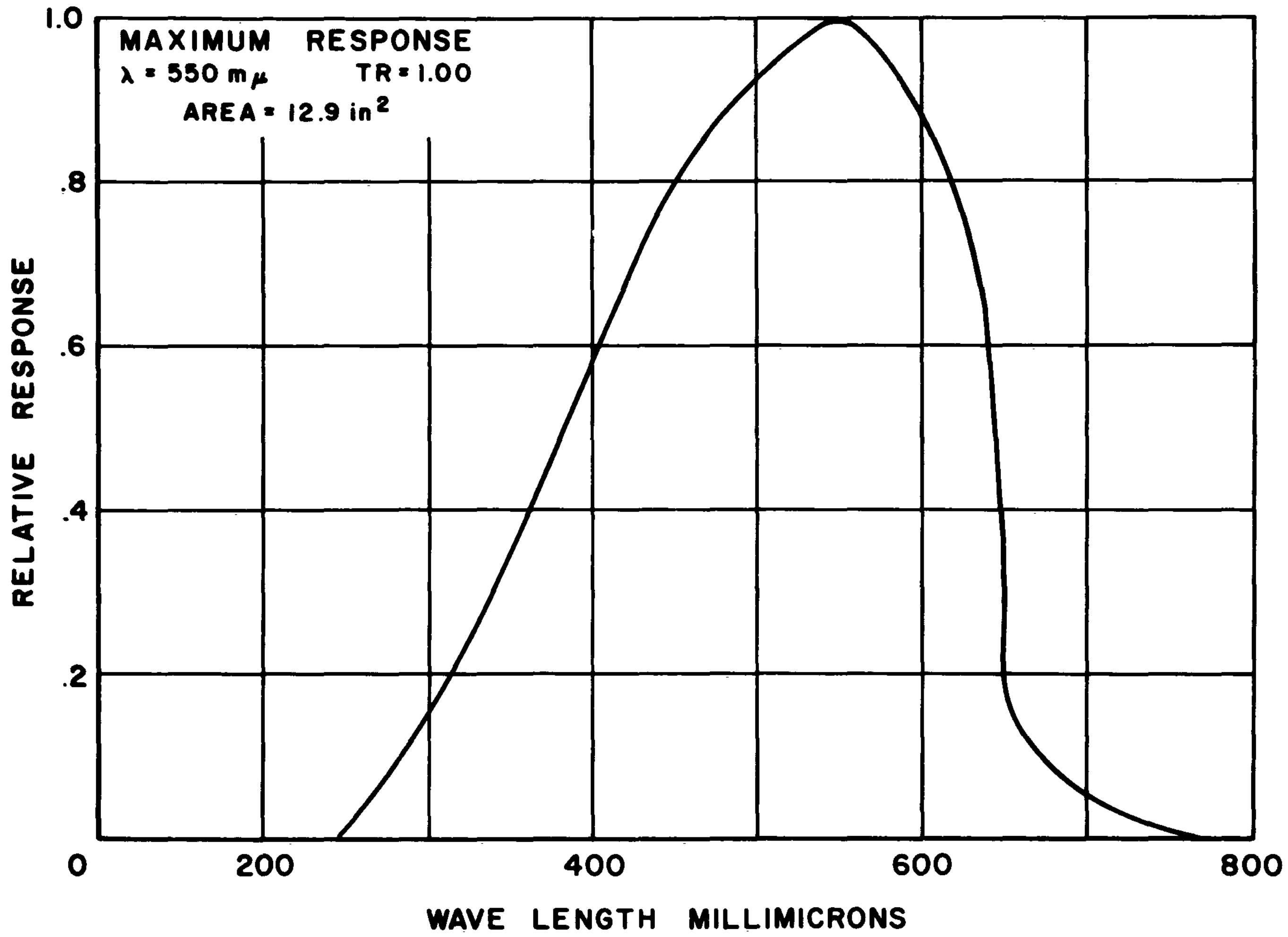
CLASS A FILM RESPONSE
(18000° KELVIN LIGHT SOURCE)

FIGURE 14



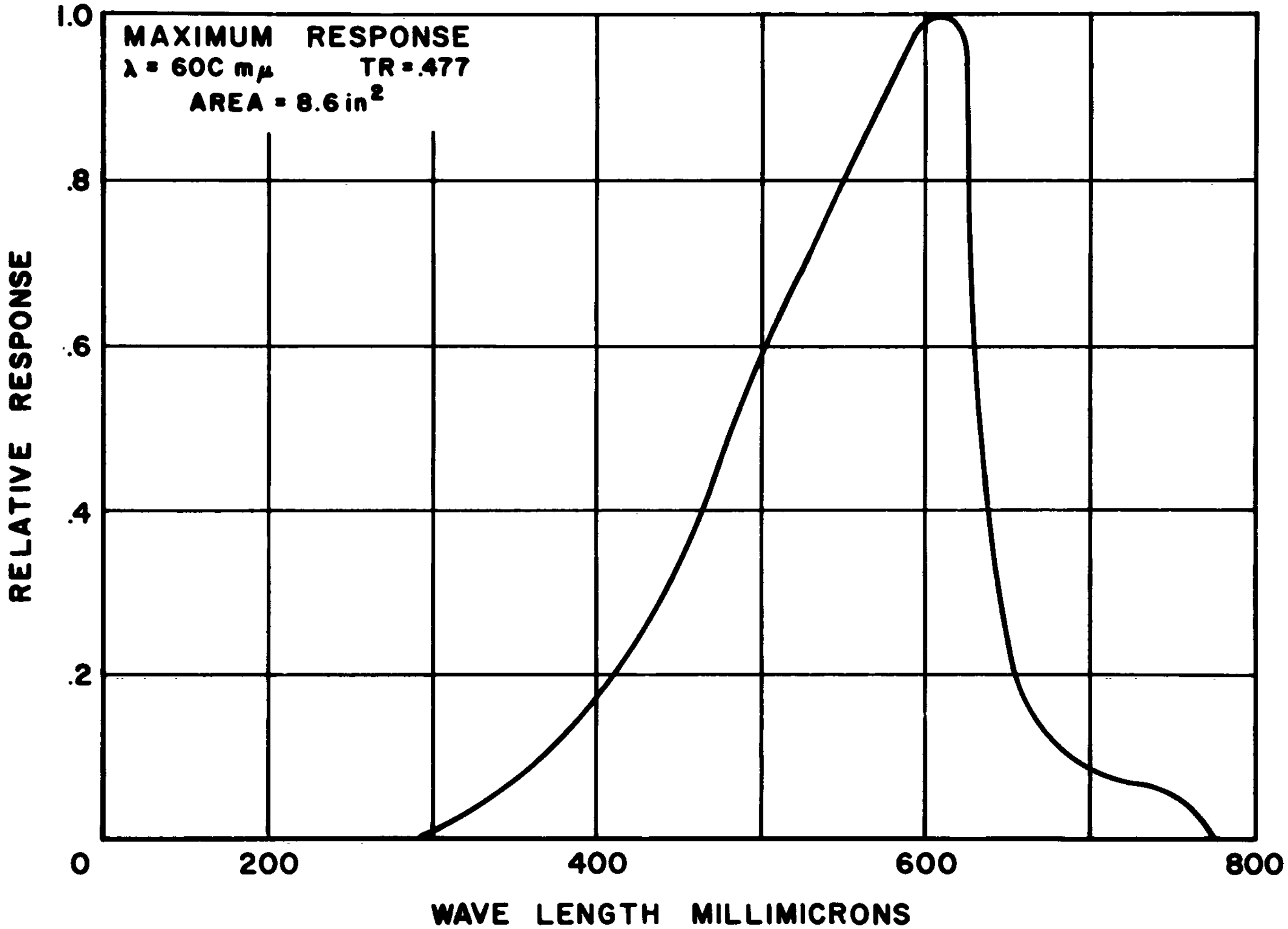
SELENIUM PHOTOCELL RESPONSE
(3000° KELVIN LIGHT SOURCE)

FIGURE 15



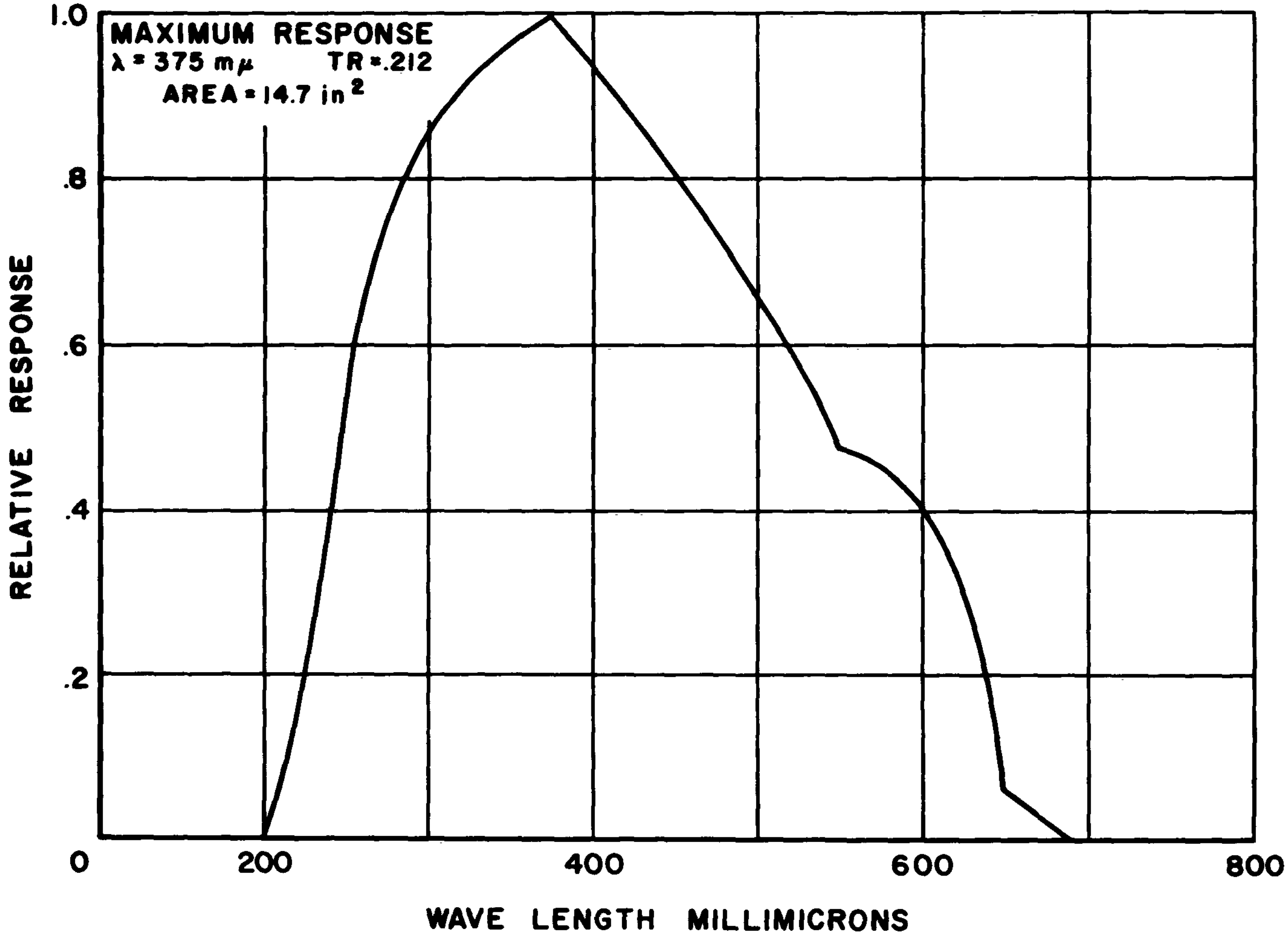
SELENIUM PHOTOCELL RESPONSE
(5500° KELVIN LIGHT SOURCE)

FIGURE 16



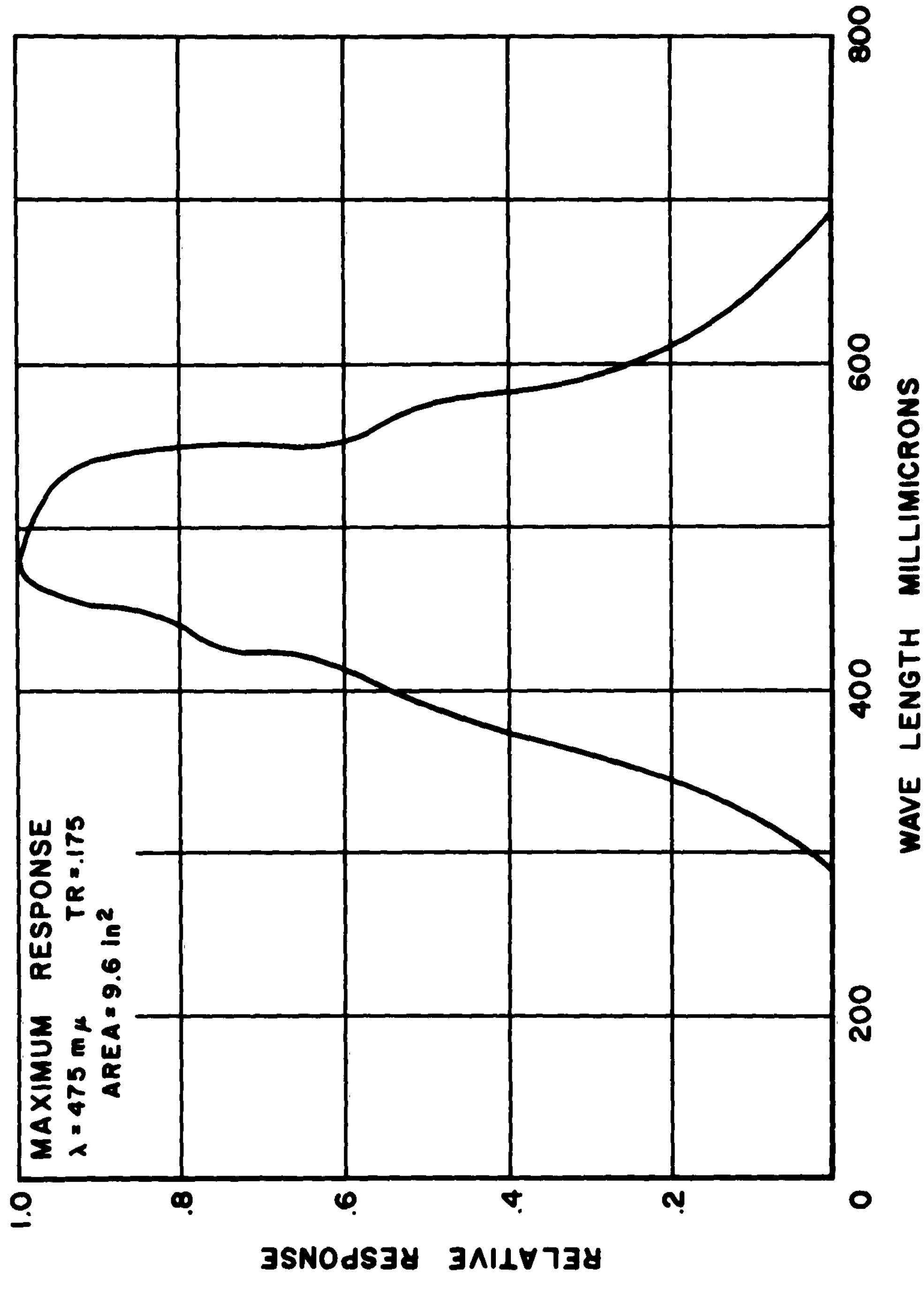
SELENIUM PHOTOCELL RESPONSE
(3000° KELVIN LIGHT SOURCE)

FIGURE 15



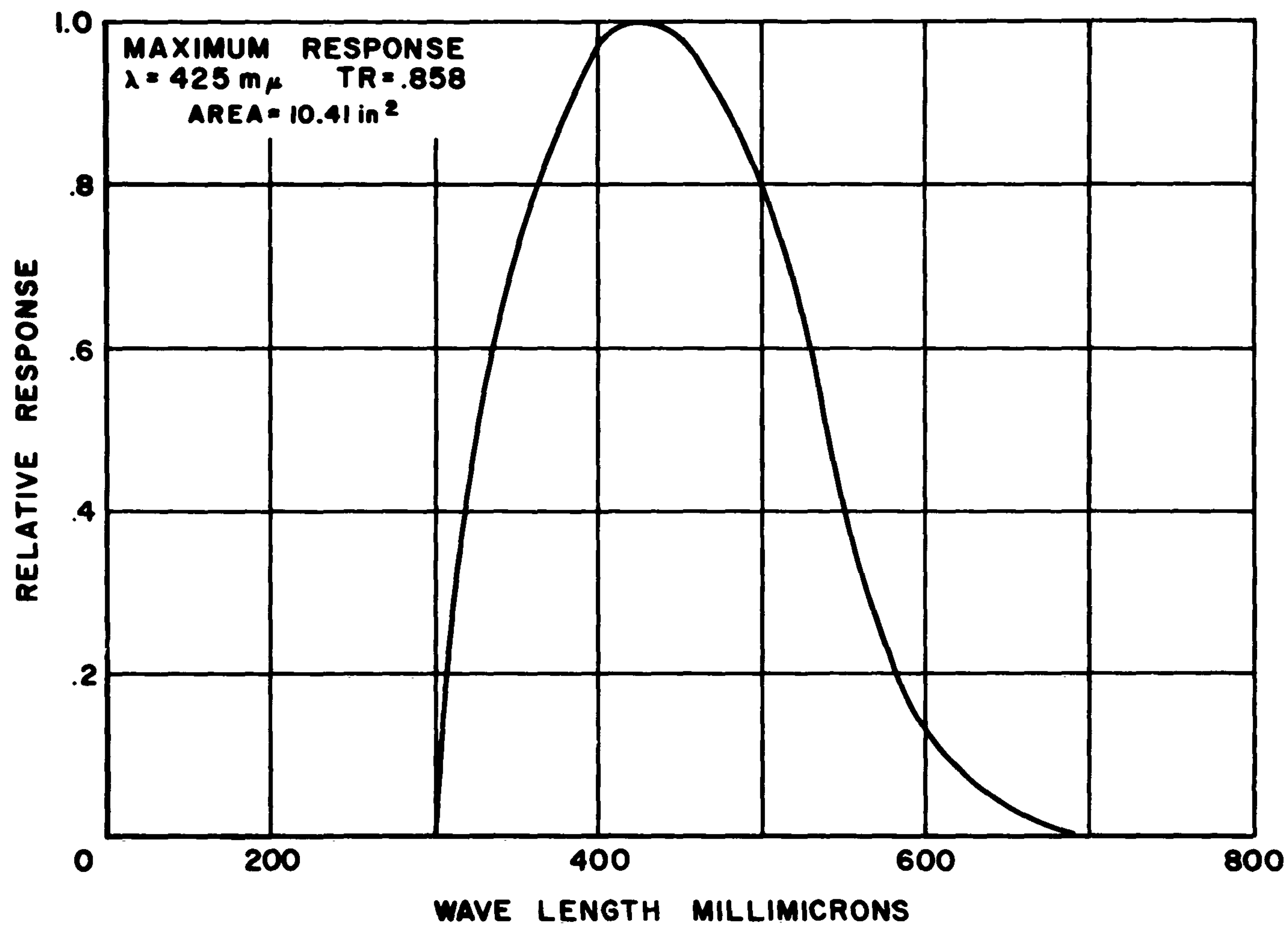
SELENIUM PHOTOCELL RESPONSE
(18000° KELVIN LIGHT SOURCE)

FIGURE 17



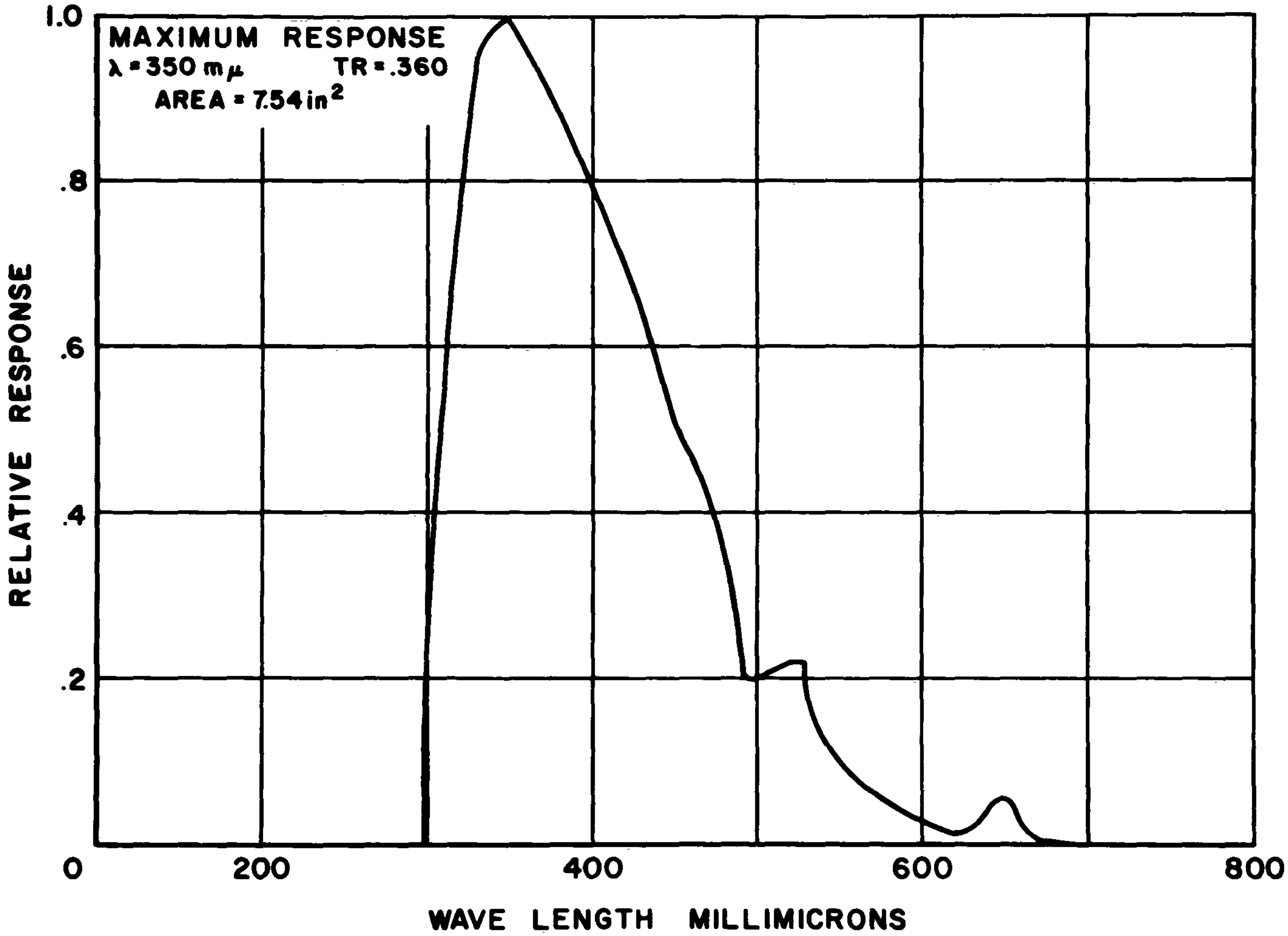
S-4 PHOTOCELL RESPONSE
(3000° KELVIN LIGHT SOURCE)

FIGURE 18



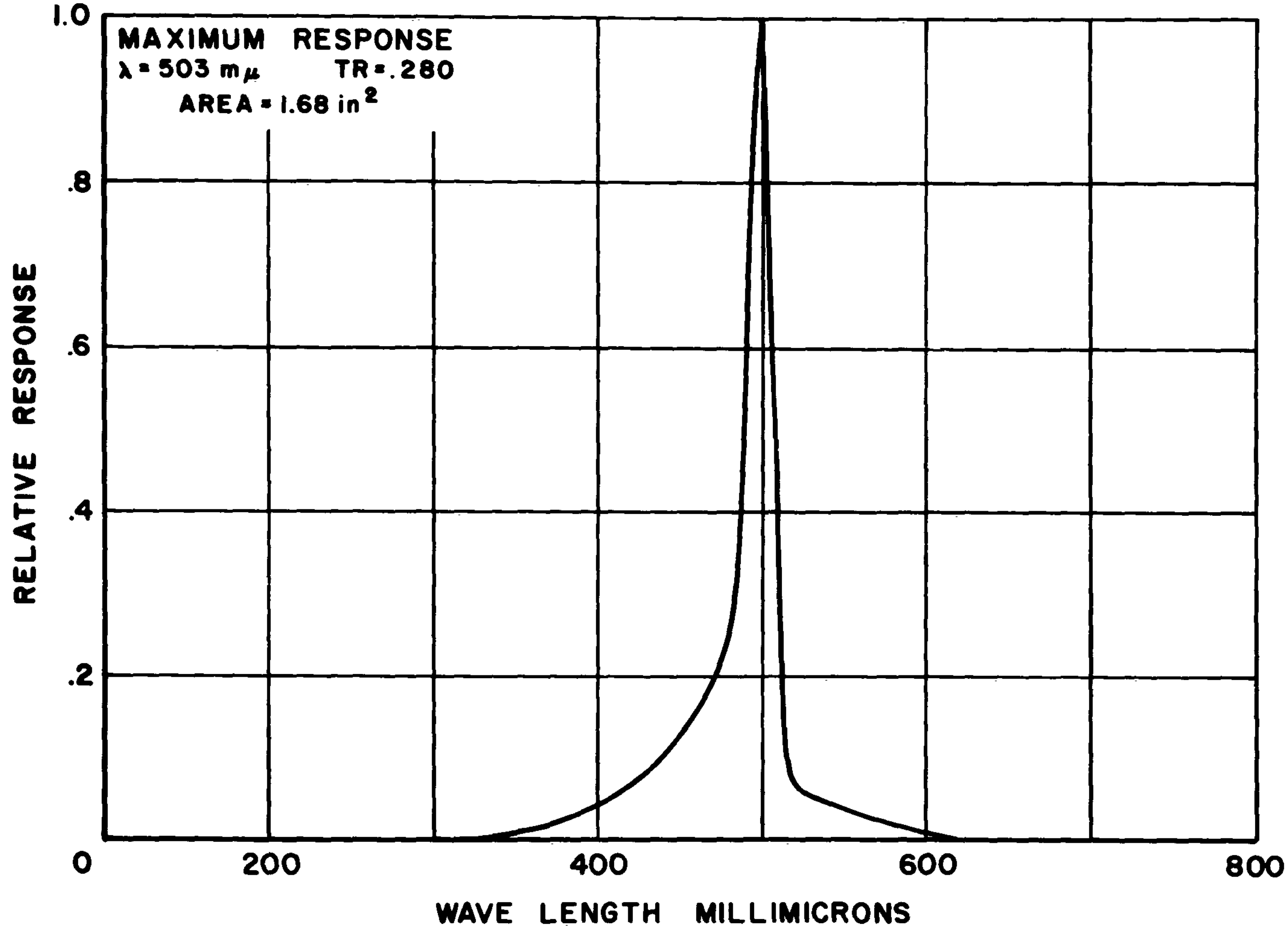
S-4 PHOTOCELL RESPONSE
(5500 ° KELVIN LIGHT SOURCE)

FIGURE 19



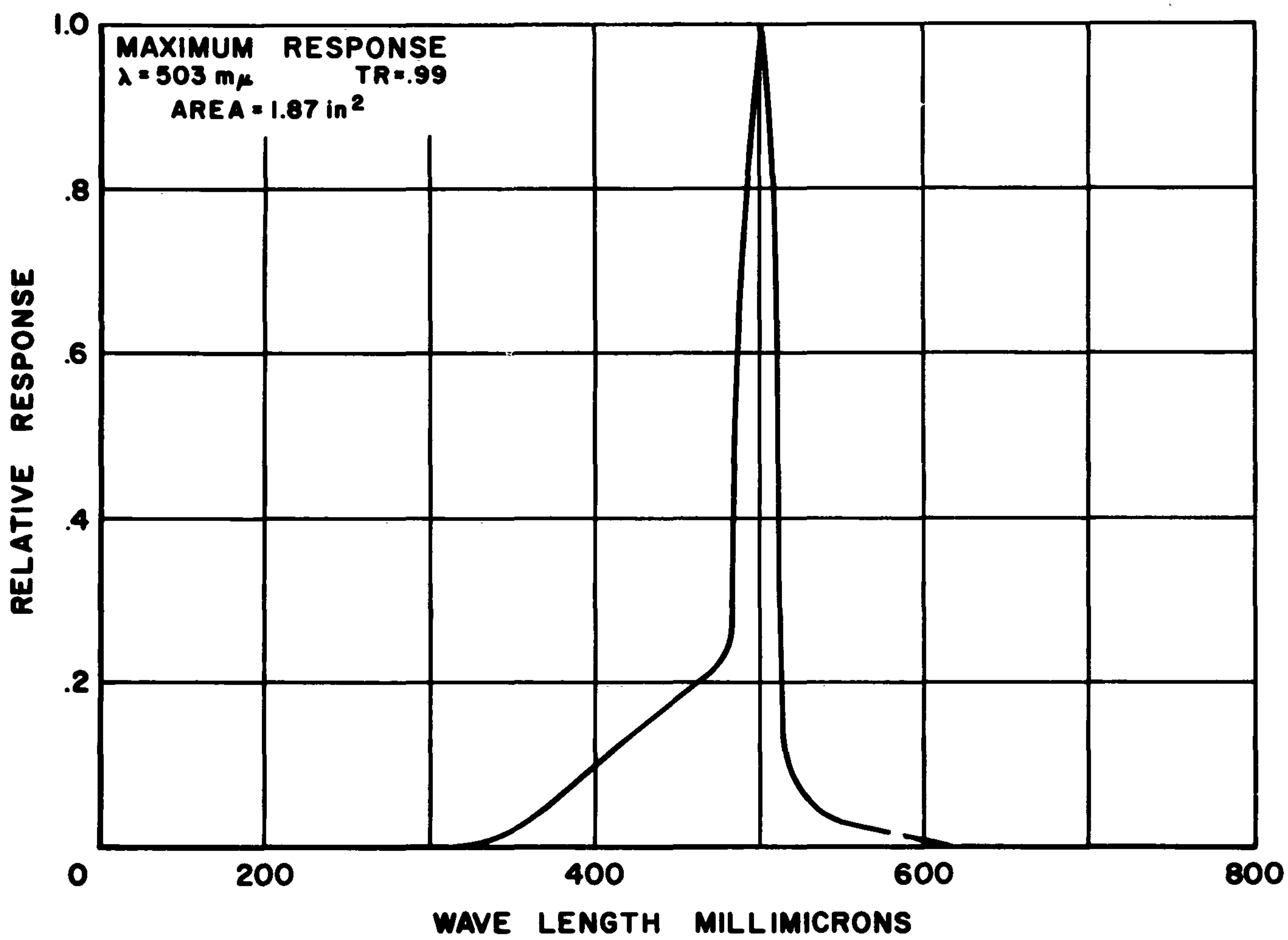
S-4 PHOTOCELL RESPONSE
(18000° KELVIN LIGHT SOURCE)

FIGURE 20



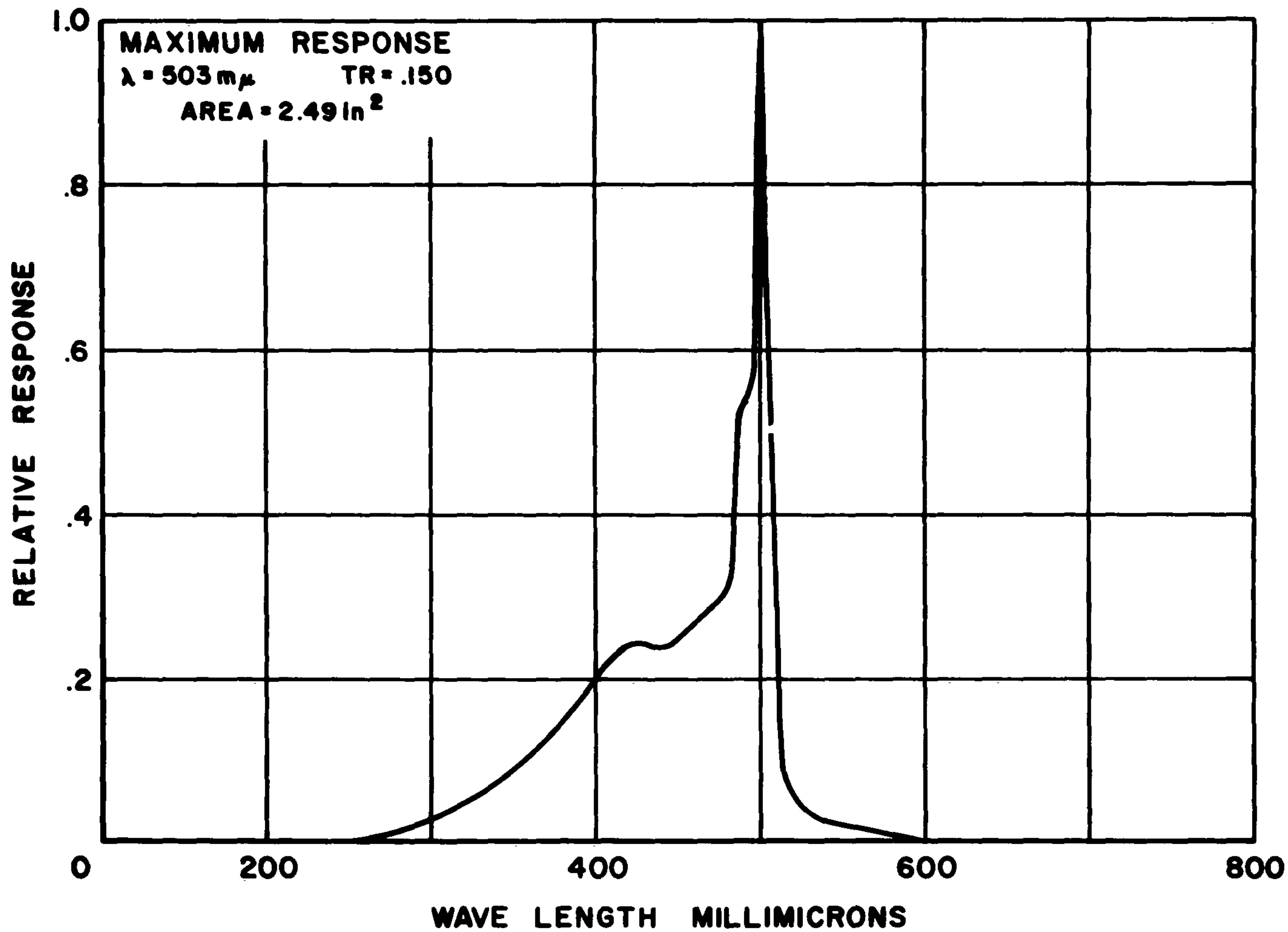
S-12 PHOTOCELL RESPONSE
(3000° KELVIN LIGHT SOURCE)

FIGURE 21



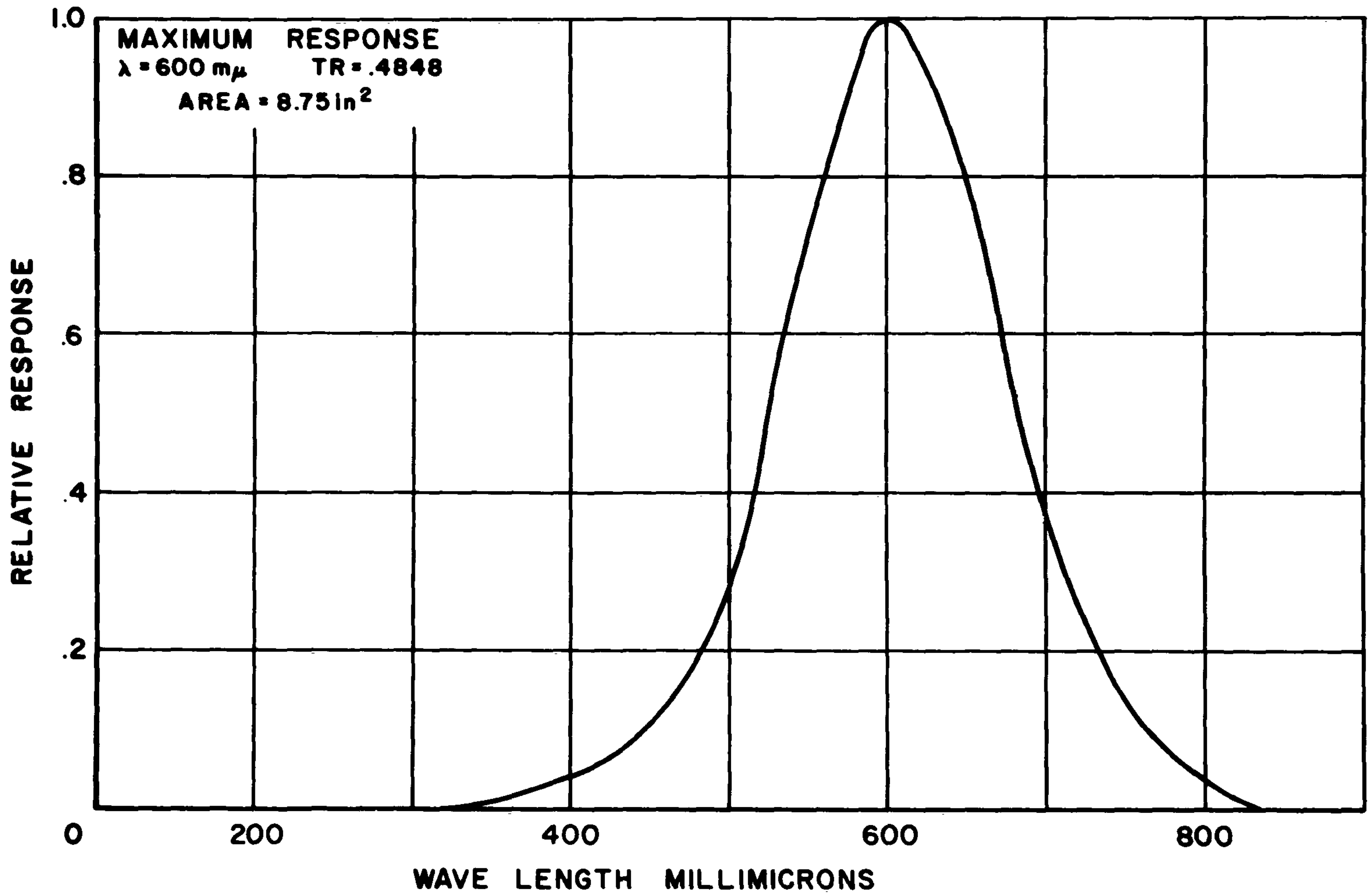
S-12 PHOTOCELL RESPONSE
(5500° KELVIN LIGHT SOURCE)

FIGURE 22



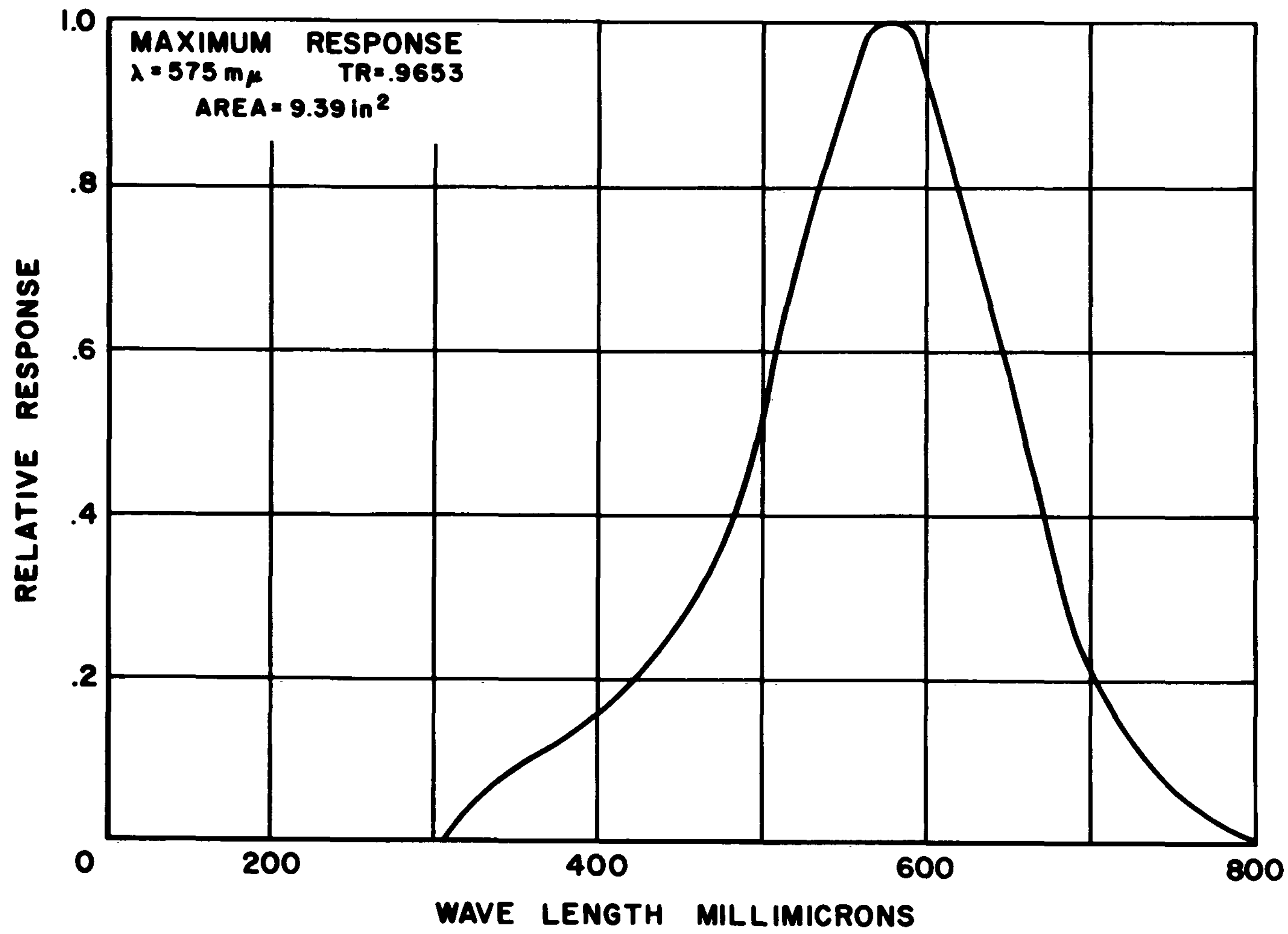
S-12 PHOTOCELL RESPONSE
(18000° KELVIN LIGHT SOURCE)

FIGURE 23



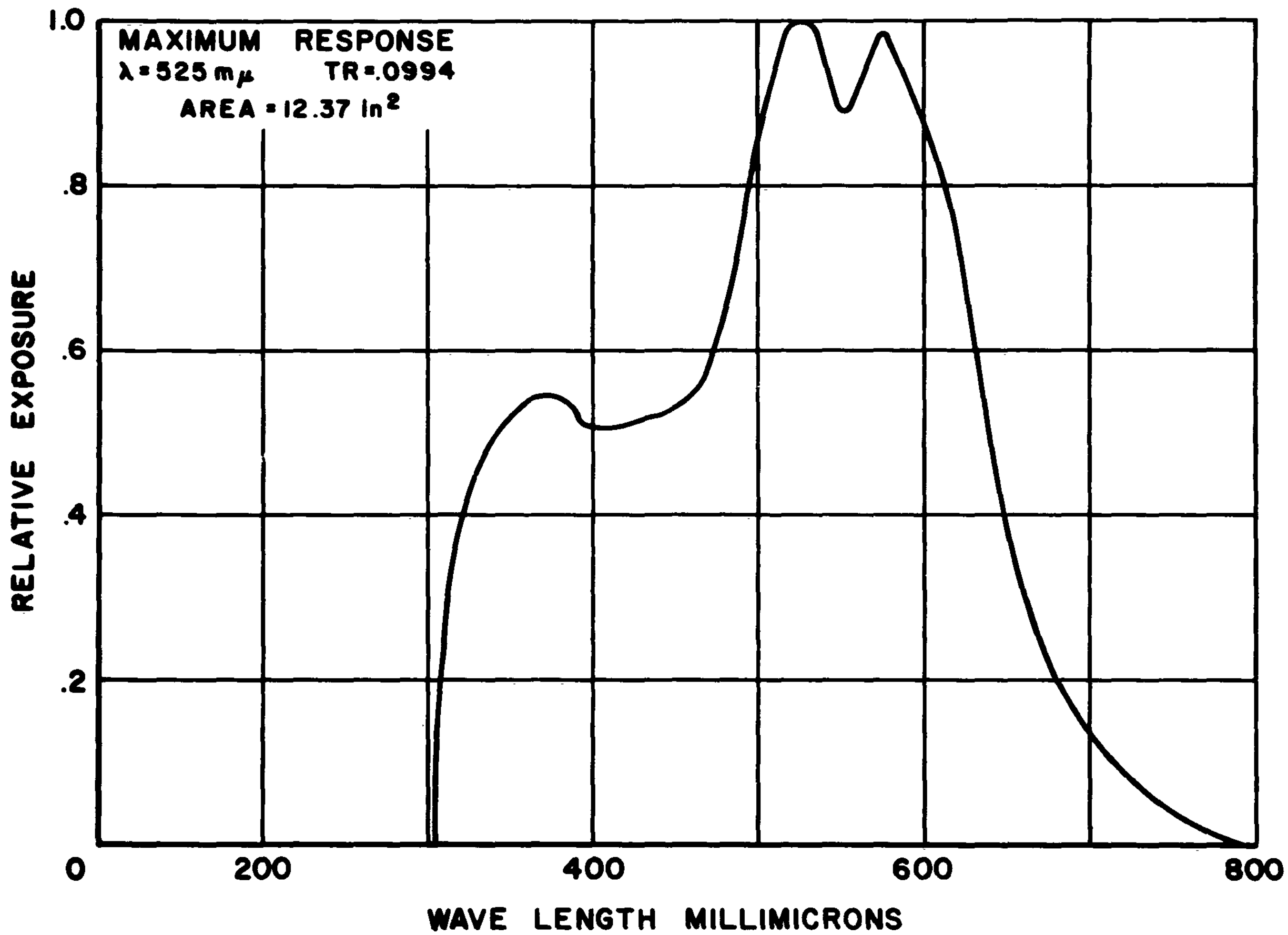
S-15 PHOTOCELL RESPONSE
(3000° KELVIN LIGHT SOURCE)

FIGURE 24



S-15 PHOTOCELL RESPONSE
(5500° KELVIN LIGHT SOURCE)

FIGURE 25



S-15 PHOTOCELL RESPONSE
(18000° KELVIN LIGHT SOURCE)

FIGURE 26

CHAPTER V

THE INDIVIDUAL TERM ANALYSIS OF THE AUTOMATIC EXPOSURE EQUATION

Section 1. "B" Term

In the second chapter, general derivation of the automatic exposure equation was presented thereby determining the limitations and restrictions necessary when utilizing this equation. In this and following sections of the report, the terms of the equation will be examined in detail.

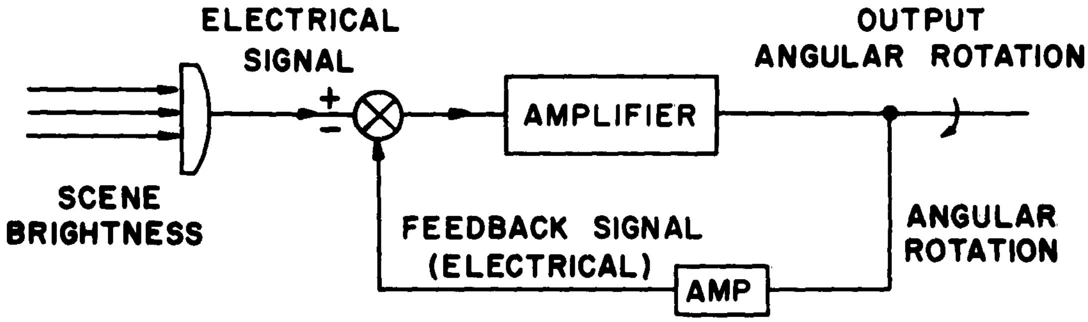
It should be remembered at all times that the prime objective of the control system is to provide a constant exposure of the film while the various parameters are changed. Translating this statement in terms of the mathematical representation using the automatic exposure equation in the form

$$E = \frac{\pi}{4} B T t S_a \frac{1}{f^2} \tag{42}$$

We find the E term must remain constant as the various parameters on the right side of the above equation vary. Once the camera is loaded and ready for operation the T and E reference parameters are fixed. Likewise, since B is the integrated scene brightness, it is a function of the environment; therefore, only the aperture and time of exposure are variable parameters. Obviously the aperture is the primary controlling parameter.

The first term to be investigated will be the scene brightness. Examination of brightness term B of the exposure equation requires a use of the photometry principles discussed in Chapter III and also that one be able to determine the effects of white light on light sensitive devices by the methods presented in Chapter IV.

Figure 27 shows the block diagram of a closed loop servo system. The input to this system is the "scene brightness" which results in an angular displacement of the aperture. Since the angular displacement is accomplished by means of an electromechanical method, it is necessary that the scene brightness be converted into an electrical signal. This electrical signal is then compared with a feedback signal. The difference between the brightness signal (electric signal) and the feedback signal is then amplified and drives the aperture until the error signal decreases below the minimum detectable level.



BLOCK DIAGRAM OF CLOSED LOOP SERVO TYPE APERTURE CONTROL SYSTEM

FIGURE 27

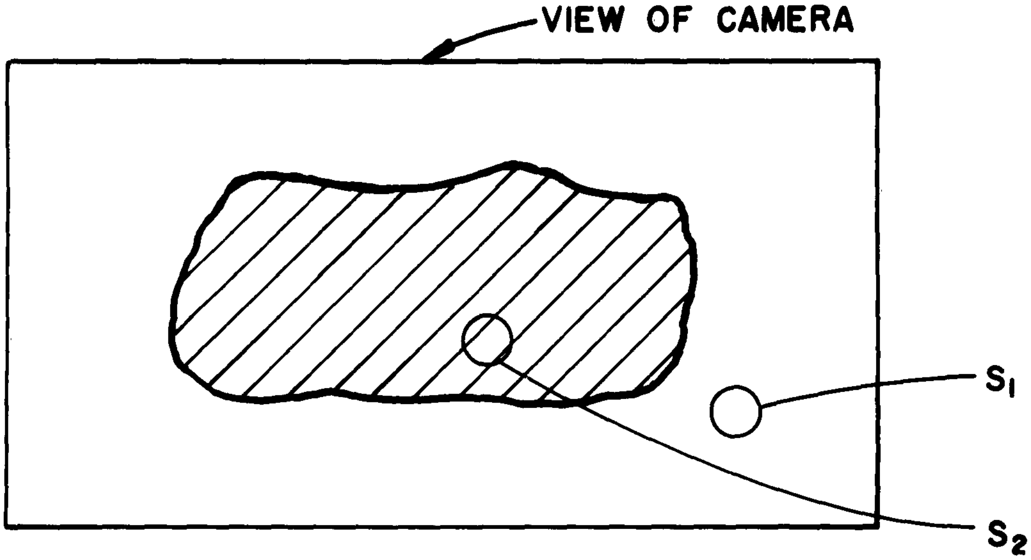
The photosensor consists of two component parts. They are:

1. The system of optics that produces the proper angle of acceptance and view area.

2. A device that exhibits photoelectric characteristics, thereby performing the light to electricity conversion of the scene brightness signal.

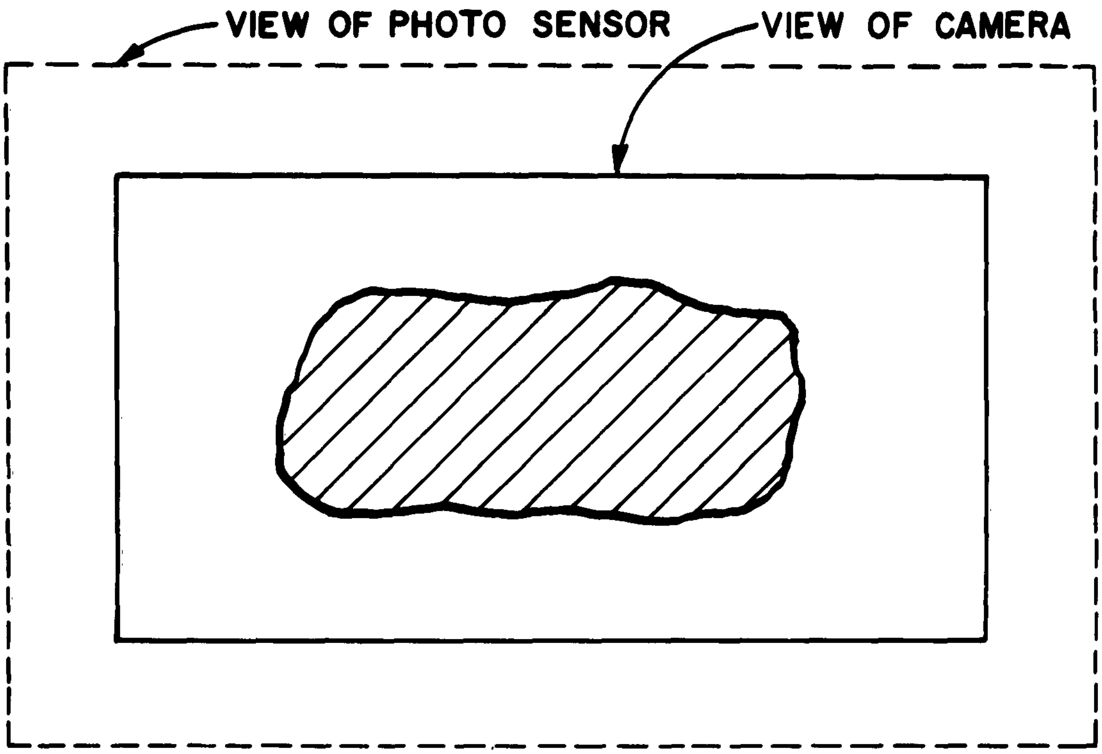
Control of the exposure is to be a function of the scene brightness. This requirement makes it mandatory that brightness information be extracted from the scene as observed by the camera and, therefore, the total view of the sensor must approximately coincide with the view on the film plane of the camera. This requirement must be met regardless of the type of sensor used. Referring now to Figure 28, the shaded area represents some object being photographed against a sky background. S_1 and S_2 represent areas which might be viewed by a photosensor having a very small angle of acceptance (relative to the angle of view of the camera). In either case, the photosensor sees either the maximum scene brightness S_2 or the minimum scene brightness S_1, and in no way can the average brightness of the complete picture area be determined from either the S_1 or S_2 view. Obviously this shows us that the area viewed by the photosensor must be at least as large as the view of the camera.

Figure 29 demonstrates the condition wherein the viewed area of the photosensor is larger than the area viewed by the camera. It is obvious from Figure 29 that the percentage of the shaded area to the total area viewed by the photo sensor is considerably less than the ratio of the shaded area to the camera view area. Therefore, the shaded area has considerably less weight in determining



S_1 AND S_2 REPRESENTS THE VIEW AREA OF SENSORS

FIGURE 28



SENSOR FIELD OR VIEW EXCEEDING
THAT OF THE CAMERA
FIGURE 29

the average brightness of the area viewed by the photosensor. From these two examples, it can be seen that the angle of acceptance must approximately coincide with the area viewed by the camera if the average brightness of the camera view is to control the exposure in all cases.

The view of the photosensor can be made to coincide with that of the camera by one of two means. The sensor may be equipped with a lens system similar to that of the camera, or a mechanical cell or barrier may be placed ahead of the sensitive element, thereby limiting its field of view. The use of a lens involves additional expense, although this problem may be overcome to a degree by the use of less expensive lenses for the sensor mechanism. The second approach is satisfactory, but suffers from certain deficiencies. If a tube or similar barrier is used, the physical length may become excessive for a very narrow field and a given photocell area. If a honeycomb barrier is mounted on the face of the cell, a portion of the active area of the cell is lost. One advantage in using a lens system is derived from the possibility of direct coupling of iris diaphragms for control of the camera exposure.

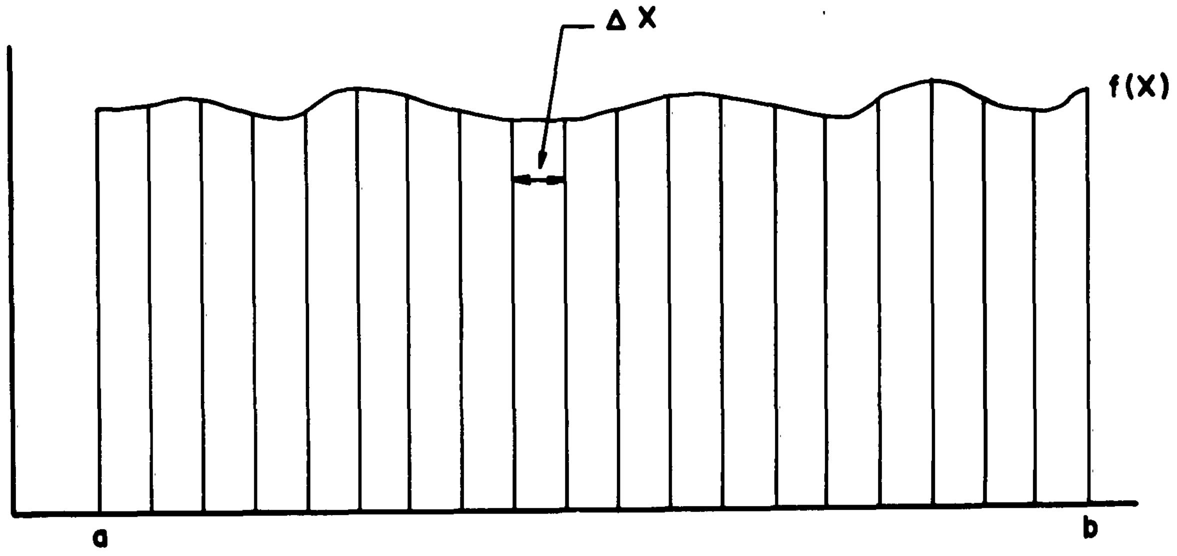
Once the proper view is impressed on the photoelectric sensor, it is necessary that an electrical output signal be a function of the integrated scene brightness. Let us now examine the fundamental operation of a photoelectric device and determine the limitations and restrictions, if any, applicable to our use. The three basic types of photoelectric devices used for this application are:

1. Vacuum phototubes. When light strikes a surface, electrons are released and produce an electric current which is a function of the light.
2. Self-generating type photocells. An emf is produced by chemical or physical reaction when subjected to light. These are normally used in light meters.
3. The photoconductive type. In this type the electrical conductivity of the cell changes when subjected to light thereby making the resistance a function of the light.

All of the above photoelectric devices have two common properties. They are:

1. The output of the cell is a function of the total light flux impressed on the active surface of the cell.
2. The output sensitivity is a function of the wave length of the light impressed on its surface.

One of the most important features of the photoelectric sensor is its ability to produce an electrical output that is an integration of the light impressed on its active area. The output of the photoelectric sensor is a function of the total light on its surface rather than the intensity of the light. If one were to obtain the integrated brightness, it would be necessary to sum up the total light flux of the area. This is the same process used when one finds the area under a curve by integration. First the curve is broken into small rectangular strips as in Figure 30.

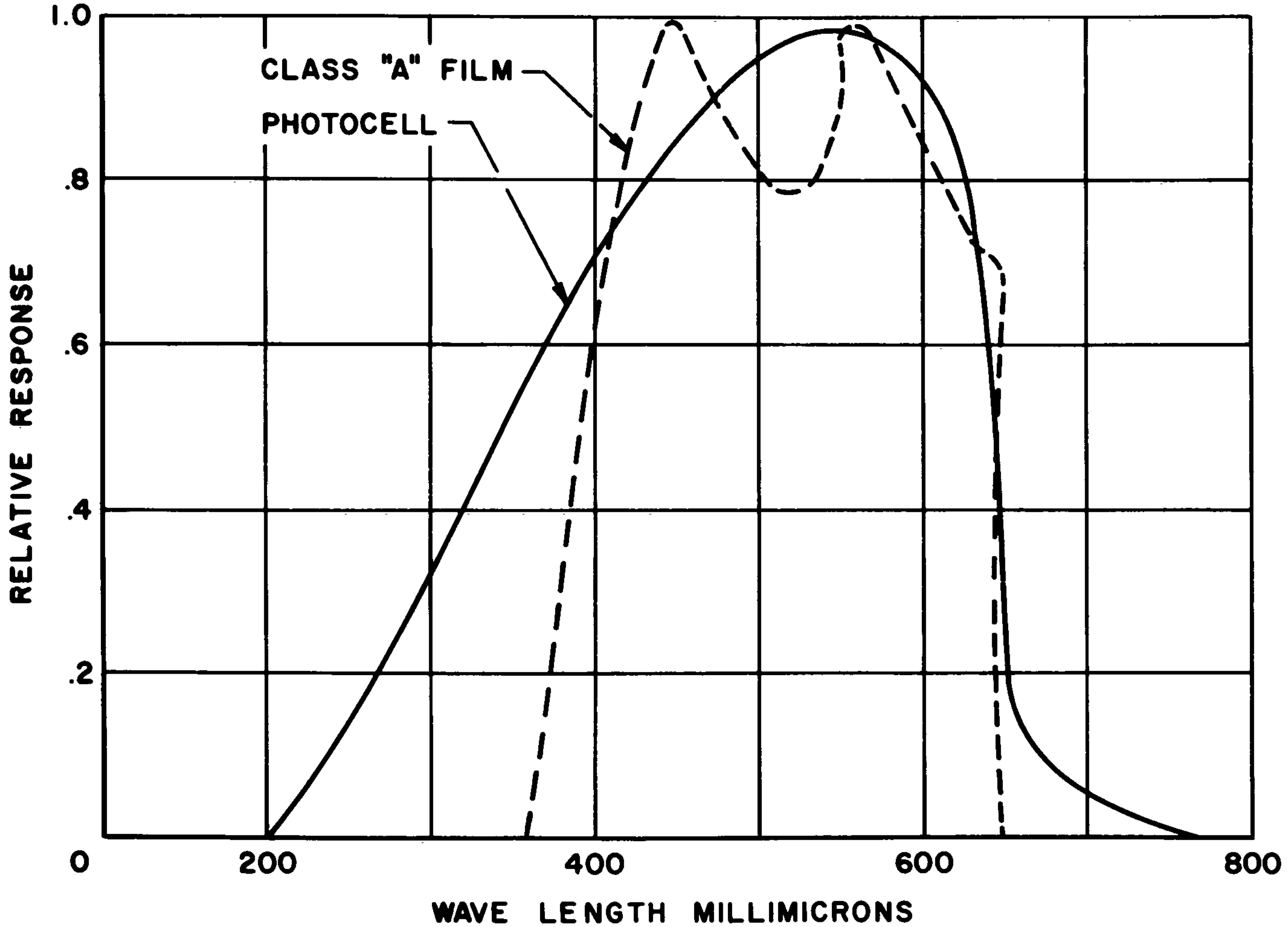


ARITHMETICAL INTEGRATION
FIGURE 30

The area of the rectangle is found as the width of ΔX is reduced to zero summing up all the rectangles. If the area under the curve a-b is divided by the length b-a, then the average area per unit length is found. In a similar manner the photocell sums up the light flux and gives an output proportional to the total light flux. If the total light flux is divided by the area of the cell, then the average flux per unit area is obtained. Since this area of the cell is constant, the average brightness so computed is proportional to the total or integrated brightness. The output (electrical) is proportional to the average brightness and also to the integrated brightness.

The second property that all photoelectric devices possess is that of the output sensitivity varying as a function of wave length. It is necessary to utilize the procedures employed in Chapter II, Section 2 to determine the output of a particular device.

Figure 31 displays the relative response characteristics of a selenium photocell and the relative response characteristics of Class "A" Type Film as function of wave length. Observation of these curves reveals that they are by no means identical. Therefore, the relative sensitivity of the film and selenium cell will vary as a function of the color temperature of the light source. The electrical output of the photocell is dependent not only upon the intensity of light but also upon the color temperature of the light exposing the film. Variation in either light brightness or color temperature will cause the photoelectric cell



NORMALIZE RESPONSE CURVES OF CLASS "A" FILM AND SELENIUM PHOTOCELL

FIGURE 31

output to change its value. In determining the action of the exposure control system, we must determine the relative change of the sensitivity of the photocell with respect to the film sensitivity. The method for determining the relative change in sensitivity area was derived in Chapter IV. The relative variation of the sensitivity of the Class "A" film and the selenium cell as a function of color temperature is shown in Table 4 below. "C" represents the ratios of the exposure of the film to the selenium output current for the same given light conditions. "α" represents the relative change of "C" normalized to "C" at 5500 ^{o}K.

TABLE 4

RELATIVE VARIATION OF SENSITIVITY OF CLASS "A" FILM AND SELENIUM PHOTOCELL AT DIFFERENT COLOR TEMPERATURES

Color Temperature (Degrees Kelvin)	C	α
3000	0.971	1.158
5500	0.838	1.000
18000	0.545	.650

The sensitivity of the photocell controls the exposure on the film, and it can be seen that the relative sensitivity of the Class "A" film is greater than the cell by 1.16 at 3000 ^{o}K. The film will be exposed with approximately 16% more light, thus exposing the film slightly more than the desired density. On the other hand when the light color temperature is 18000^{o} K, the relative sensitivity of the photocell is 1.53 times greater than the film. The film will, therefore, be exposed as if the light were 1.53 times greater than actually exists thereby causing the film to be underexposed. Several rather important conclusions can be derived from the above information. They are:

1. The film and photosensor relative response curve must be as identical as possible (if necessary filters should be used to shape photosensor to curve of film).

2. The effect of color temperature on the accuracy of the control system will depend upon the "degree of identity" of the relative response curves of the film and photosensor.

3. For data shown, the difference of response between the 5500^{o} K light source and the 3000^{o} K light source was approximately 16% whereas the difference between the 5500^{o} K and the 18000 ^{o}K was 53%. This indicates that if the systems were checked with

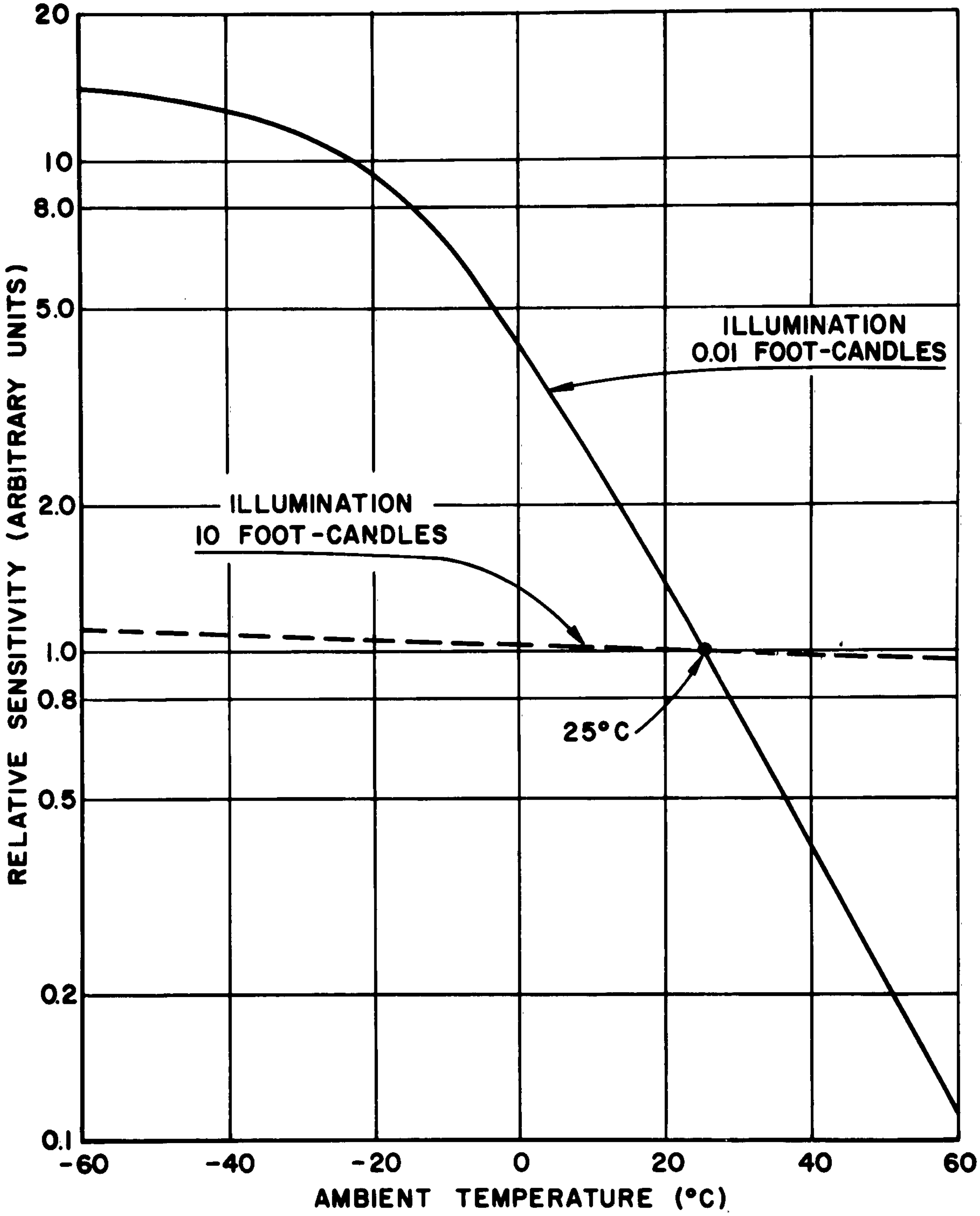
a light source of 3000° K the system error due to the color temperature effect would be less than 1/3 f stop. The film would be exposed to approximately 16% more radiant energy than if tested at the required color temperature of 5500 °K. This would produce a density of approximately 0.08 greater than at the required test specification if the system is in every other way functioning properly. Chapter II shows the relative response for Class "A" film and the response of the following photoelectric cells:

1. Selenium Cell
2. S-4 Phototube Coating
3. S-12 Phototube Coating
4. S-15 Phototube Coating

Without additional filtering, the S-15 response gives the most desirable response characteristics over the color temperature range of 3000° K to 18000° K for Class "A" type film.

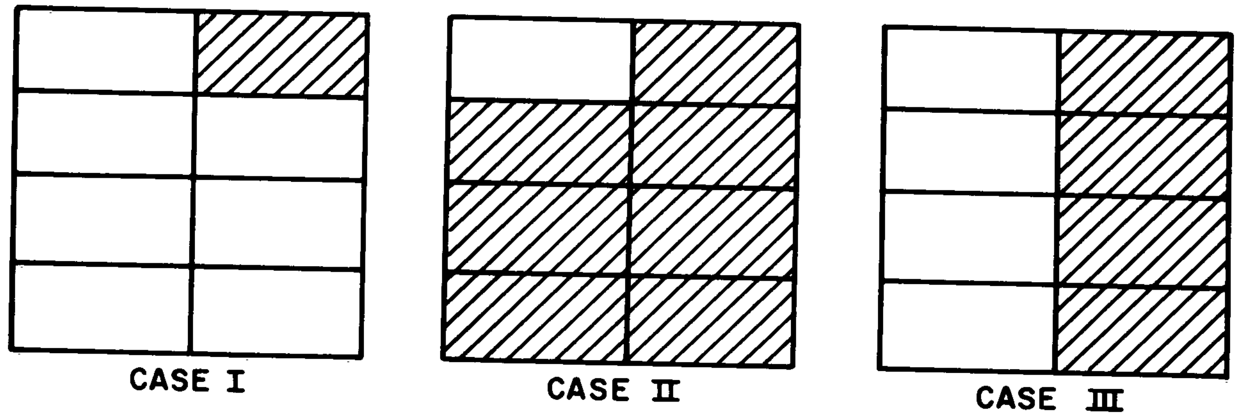
The photoelectric sensor provides the method of translating light information into an electric signal. The constant of conversion must remain the same over the required environmental conditions. Figure 32 shows a graph of the relative change in sensitivity of the photoconductive cell (having an S-15 response characteristic) as a function of temperature and the light level impressed on the cell. Notice that the operation of the cell at light levels as low as 0.01 foot candles is entirely unsatisfactory unless it is mounted in an accurately controlled oven at 25 °C.

Until now, the discussion has been predicated upon the use of an averaging type of brightness sensor. As was pointed out in Chapter II, emulsions are characterized by a region of proportional representation which extends over a wide range of exposure levels. In most uses of photography wherein automatic exposure control is of greatest interest, the scene will consist of information elements of varying brightness. It is therefore, desirable to adopt an aperture setting which will yield to highest probability of maximum true information representation. It has been found that resolution is somewhat enhanced in negative emulsions by slightly extending the lowest exposure levels into the knee of the D log E curve. For several emulsions, however, the tolerances are such that the exposure range should be centered in the "straight line" portion of the D log E curve. Such a requirement can be met in one of two ways. If it is known that the brightness range of the object scene is small, then one may use an averaging device with good expectation of acceptable results. One failing of the averaging type of sensor can be readily demonstrated. In Figure 33 is shown a very simple scene of varying brightness levels, with different area distributions.



RELATIVE SENSITIVITY OF THE S-15 PHOTOCONDUCTIVE CELL, TYPE NO. 7163

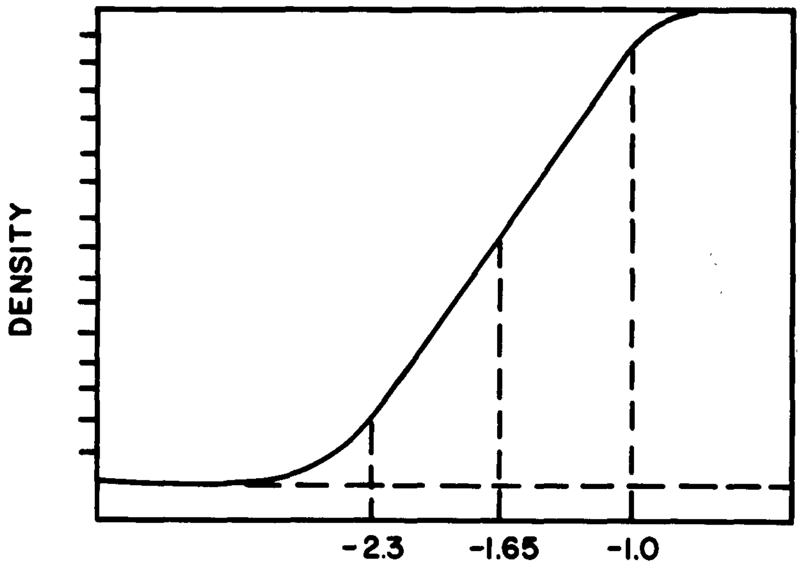
FIGURE 32



SCENE OF VARYING ILLUMINATION AND IDENTICAL RANGE OF ILLUMINATION

FIGURE 33

In each square, assume the dark area to correspond to an image plane illumination level of 0.5 m.c. and the light area to an image plane brightness level of 10.0 m.c. If the latitude of the emulsion to be used is 1.3 log exposure units, then it is obvious that the film is capable of rendering the above scenes proportionately. Let us assume the D log E characteristic of the film to be as shown in Figure 34. Furthermore, for simplicity, take the exposure time equal to 0.01 second.



HYPOTHETICAL D LOG E CURVE
FIGURE 34

The geometric mean of the maximum and minimum exposure levels is found by

$$E_o = \sqrt{E_{MAX} \times E_{MIN}}$$

and corresponds to the log exposure value -1.65. This point represents the optimum reference point for the conditions stated, but is attainable only at considerable sacrifice of the simplicity of the sensing system. For the time being, however, let us pursue the reaction of the averaging system.

The averages observed for the three cases are:

Case 1 $\quad 70.5/8 \simeq 8.8$

Case II	13.5/8	$\simeq$	1.69
Case III	4.2/8	$\simeq$	5.3

If now the system has been designed to vary the aperture until the average exposure corresponds to the center of the straight portion of the D log E curve (log E-1.65), then we can compute the range of exposure above and below this point. Since the total range of illumination is 0.5 to 10 m.c., we can construct the following table:

TABLE 5

EXPOSURE RESULTING FROM USE OF AVERAGE ILLUMINATION SENSOR, BASED ON FIGURES 33 AND 34

Case	Min Log E for Proportional Density	Max Log E for Proportional Density	Minimum Log E (Actual)	Maximum Log E (Actual)	Results
I	-2.3	-1.0	-2.89	-1.59	Under-exposed Low end
II	-2.3	-1.0	-2.18	-0.88	Over-exposed High end
III	-2.3	-1.0	-2.68	-1.38	Under-exposed Low end

Note that only Case II is approximately correct. The example given is somewhat artificial, but some important points are made. First, the averaging type of sensor produces an output which is energy balanced. In other words, the amount of energy density area product above the average is equal to that below. The average so measured will lie between the maximum and minimum, but its exact location depends on both the geometrical distribution of brightness and the magnitude of brightness.

A second method of determination of B_o, the reference brightness, would be to employ a scanning sensor which would scan the object scene by the motion of a very small sensing spot. Such a system would determine the maximum and minimum brightness levels and from these establish the geometric mean of the extreme for the reference level. As one can see such a technique is considerably more involved than that used in simple averaging. On the positive side for averaging, however, aside from simplicity, are several practical arguments. In many applications, the range of brightness in the average subject is very low compared to the dynamic capability of films. In many other applications, the extremes of lighting levels are relatively unimportant and contrast may be really sacrificed at either end of the range providing the essential information is contained within a reasonable range of the average brightness. In still other applications, such as those encountered in photography of missiles during tests, the entire viewed scene is dominated by an area of intense light. In such cases, the primary object of interest may be the flame itself or objects so near the flame that their brightness is very high. In such an application, the aperture control will react to the high intensity light and change the aperture until the reference exposure is attained. At this setting, which in this instance would correspond to an average brightness somewhat less than the maximum, useable film dynamic range is still available above and below the reference level. The reference level will be reached on the basis of a high brightness level and severe underexposure of darker scene elements will result. In this case, however, this side effect is of relatively less importance.

In many aerial applications, target contrast ranges may also be quite low, and the average light level becomes a better approximation to the ideal as the scale of luminance decreases. Several sources gives average ranges of contrast in aerial photography as from 10. 1 to a minimum useable value of 1. 5 to 1. Contrast decreases as altitude increases, with higher contrast observed for built up areas. In cases of such low contrast, the average brightness seems to be a satisfactory standard.

It should be noted here that while the discussion has been based primarily on the basis of image forming light, that the general results apply to cases where there is flare light originating from the atmosphere outside the camera and to some extent to internally reflected light insofar as the internal flare light of camera and sensor are similar. Flare light has the general effect of reducing contrast of the image and since the magnitude of flare light can usually be expected to be on the order of the minimum light level encountered, will not greatly affect the choice of a reference brightness. Filters, if used, affect the intensity and spectrum of the light incident upon the emulsion. The exposure will thereby be affected and adequate corrective steps must be taken in setting up the exposure control system, including the use of appropriate filters.

In summary, there are several points which can be made in regard to the effect of object brightness upon the design, test, and evaluation of automatic exposure control systems.

1. The angular area constituting the sampled area must coincide with that seen by the camera. In simplest terms, the acceptance angle of camera and sensor must be identical and the optical axes of the two must be aligned.

2. Since the color temperature of light varies, best results will be obtained if the spectral response of emulsion and sensor are identical (or as nearly so as possible). Both film and sensor react to total energy density in the microscopic sense and are inherently heterochromatic.

3. The design should include accommodation for the variations in light to electrical signal transformation sensitivity which arises from environmental conditions such as temperature and light level.

4. The method of measurement of object brightness should be determined on the basis of expected object characteristics and allowed tolerances versus the relative complexity of various techniques.

5. Variations in sensor-film combined response to the effect of light, physical handling, and environment are factors which lie outside the closed loop in a servo type system. For this reason, these factors cannot be accommodated by other than careful matching and adjustment of system constants.

CHAPTER V

THE INDIVIDUAL TERM ANALYSIS OF THE AUTOMATIC EXPOSURE EQUATION

Section 2. "K" and "S_a" Terms

In an earlier section, the equation

$$E = \frac{\pi}{4}\left(\frac{B\,t\,T}{f^2}\right) \tag{43}$$

was developed. In the derivation of the automatic exposure equation, a constant K was employed so that the equation could be written in the form

$$f^2 = K B t S_a \tag{44}$$

and it becomes of interest to analyze the meaning of and relationship between the K and S_a terms. Returning to the more basic form of Eq. (44) one can write

$$f^2 = (K_L)(K_E)(K_N)\,B\,t \tag{45}$$

where the subscripts refer to the lens transmission factor (L), and emulsion constant (E), and a numerical factor (N) to account for the units employed. The desired exposure is implicitly expressed in K as

$$K_E = \frac{\text{APPROPRIATE CONSTANT}}{E} \tag{46}$$

Eq. (45) may now be rearranged and written, using our latest nomenclature

$$\frac{1}{K_E} = \frac{B\,t\,(K_N)(K_L)}{f^2} \tag{47}$$

and the equation is reduced to its basic form. This form may be described by the following statement:

> At the balanced condition the image plane energy is equal to a precomputed value. Note that there is no true balance in the exact sense, due to the limitations of the sensing and exposure mechanisms which have been described previously. The performance of automatic exposure control, excepting the electromechanical limits of the system, is no better than the system constants as measured or otherwise determined in advance.

K_E therefore must be obtained, in the strictest sense, from the D log E curves describing the performance of the emulsion. On the other hand, using personnel are usually required to operate on the basis of film speed ratings such as WESTON and ASA. It is, therefore, of interest to examine K_E in the form of Eq. (46). In this case, we may take the film speed to be indicative of a reference exposure. Note that this is not necessarily the desired exposure and appropriate allowance must be made in K for the correct exposure desired. In the WESTON system

$$S_W = \frac{4}{E} \tag{48}$$

where E is an exposure yielding a density equal to gamma, Eq. (43) then may be written

$$f^2 = \frac{\pi}{4}\left(B T t \frac{4}{E_{REF}}\right)\left(\frac{1}{4}\right)$$

$$f^2 = \frac{\pi}{16} B T t S_W \tag{49}$$

If time, brightness, and reference exposure are in consistent units, we can effectively translate the speed measurement exposure by multiplication of the right hand side of Eq. (57) by an appropriate constant. Assuming that the point on the D log E curve corresponding to the WESTON speed measurement ($D = \gamma$) lies on the straight line portion of the curve,

$$\gamma \operatorname{Log} E - \gamma \operatorname{Log} i = \gamma - D_{FOG} \tag{50}$$

where E is the measured exposure for $D = \gamma$ and i the inertia of the emulsion as we have defined it previously. Then from Eq. (50)

$$\operatorname{Log} E - \operatorname{Log} i = 1 - D_{FOG} \cong 1 \tag{51}$$

and the measured E corresponds approximately to a point one log exposure unit greater than the inertia. If this value of E were then chosen as the reference E in Eq. (49), then less than a ten to one brightness range can be accommodated in proportional reproduction below the measured brightness level. One advantage of an adjustable "constant" therefore becomes clear. One must be very careful of the units employed in arriving at values for the constant term. In proceeding, let us retain Eq. (43) in the form

$$E = \left(\frac{\pi T}{4}\right) \frac{B t}{f^2} \tag{52}$$

and dispense, for the moment, with the artificiality of the film speed rating. The system of units which have evolved in light measuremen' annot conveniently be treated in the ordinary dimensional sense due to the cause and effect relationship which some of these units exhibit. The above equation states in symbolic form that a source of B units of brightness will, in time t, result in the delivery of E units of exposure, under the conditions specified by the equation.

The units of measurement, however, produce a certain amount of confusion. In our original development we have employed, by implication,

$$\begin{aligned} B &= \text{candles/square meter} \\ E &= \text{meter-candle-seconds} \\ t &= \text{seconds} \end{aligned} \tag{53}$$

Let us now examine Eq. (52) for dimensional equivalence. B is a measure of luminance, and E a measure of an illuminance-time product. We are then faced with an apparent dimensional anomaly unless we recall the common factor-flux. Flux is a measure of the rate of flow of radiant energy. A point source of one candle intensity radiating uniformly emits 4π lumens of flux. Since there are 4π steradians of solid angle about a point, one candle radiates one lumen of flux per solid angle. Therefore, when the units of Eq. (53) are used, Eq. (52) is dimensionally correct. Assuming for the moment that T = 1,

$$f^2 = \frac{0.786\,Bt}{E} \tag{54}$$

If now we wish to employ the WESTON speed rating, use of the relationship $S_W = 4/E$ results in

$$f^2 = 0.1985\,B\,t\,S_W$$

but in this case we should multiply the right hand side of the equation by an optional constant K^1_o to indicate our right to change the reference exposure at will. We then have

$$f^2 = K'_o\left[0.1985\,B\,t\,S_W\right] \tag{55}$$

where we have now included the lens loss factor, T. Another unit of object luminance encountered is the foot-lambert. This unit is equivalent to the luminance of a surface emitting $\frac{1}{\pi}$ candles per square foot of projected area. Therefore, if all other units remain the same and T be absorbed into K_o,

$$f^2 = K_o\left[0.672\,B\,t\,S_W\right] \tag{56}$$

we can now construct a table of values for the constant as follows assuming the lens transmission factor to be absorbed in K_o. Only the most common cases are considered. (t is seconds throughout)

B	Candles/sq foot	foot-lamberts	candles/sq meter
S_a	Weston ASA Index	Weston ASA Index	Weston ASA Index
K	$2.11\ K_o$ $1.69\ K_o$	$0.672\ K_o$ $0.538\ K_o$	$0.196\ K_o$ $0.157\ K_o$

The values of K for the ASA Exposure Index is derived from the approximate relationship

$$\text{Weston Speed} = 0.8 \text{ ASA Index}$$

As we have stated, the inclusion of the constant K_o signifies our right to deviate from the exposure dictated by the film speed rating. T indicates the loss in transforming from object luminance to image illuminance. It is at this point that the simple mathematical model fails, and the actual values to be employed must be based on experiment. For reasonable universality of application, the arbitrary constant must be adjustable over a range sufficient to allow for lens loss and for a reasonable amount of latitude in the selection of the reference exposure. These factors depend upon the lens and camera employed and the specific application for which the camera system is intended. In certain application, the use of filters on both sensor and camera lens permits an implicit correction for filter factor and such a correction is not necessary within the system equation. For example, if a system employing identical lenses on sensor and camera is operated with direct coupling of iris diaphragms, then the system is self-compensating if identical filters are employed on each lens. The photoelectric sensor (assuming a reasonable match to the film spectral characteristics) automatically increases the aperture to correct for the filter loss. If the sensor cannot accommodate a filter, a correction must be made by adjusting the constant in the exposure equation.

In automatic exposure control systems intended for use with airborne gun cameras, it has been experimentally determined that the equation produces acceptable results when in the form

$$f^2 = 0.85\, B\, t\, S_w \tag{57}$$

where B is given in foot-lamberts and S_w the Weston Speed of the film employed. In this case, a range of K from 0.3 to 1.3 was required, based on experimental findings. Using the form of Eq. (56) then, the given range of K yields approximately

$$0.45 \leq K_o \leq 1.94$$

for a range of K_o (and K) about 4.33 to 1. As earlier, the true value of K depends upon the units of measurement employed.

The uncertainty in the establishment of K then amounts to uncertainty regarding the transfer of light through the lens system. As pointed out in Chapter II, one can define a desired operating point on the D log E curves and transform this point into a function of the film speed by the use of an appropriate constant multiplier. If the transmission characteristics of the lens are determined experimentally then K can be chosen. Unfortunately, other possible parameter variations render efforts toward too high a level of precision useless. In the design of multiple purpose exposure controls therefore, the constant must be adjustable to provide for various operational conditions.

A few words might be said regarding the measurement of film speed and its effect on the selection of the K term. The various methods of measuring speed will not be discussed except to the extent of pointing out that various methods are used for different purposes and that there is no analytical method of comparing speed measured by different techniques. The speed ratings are stated as the product of a constant by the reciprocal of a reference exposure in all cases. The reference exposure, however, is in all cases different from that which one would choose as ideal for a scene of reasonable scale of luminance. The constant multiplier in the system equation must be changed twice, in a manner of speaking, to convert from one film speed rating to another rating in a different system. The numerical transformation due to the empirical differences in ratings must be made as in any transformation from one frame of reference to another. To be exact, however, one should then check the apparent operating point on the D log E curves for reasonable exploitation of the emulsion latitude. As was mentioned in Chapter II, film characteristics are subject to variation due to storage conditions, aging and manufacturing tolerances. For high tested precision work samples should be tested frequently in order to maintain reasonable knowledge of the true emulsion parameters.

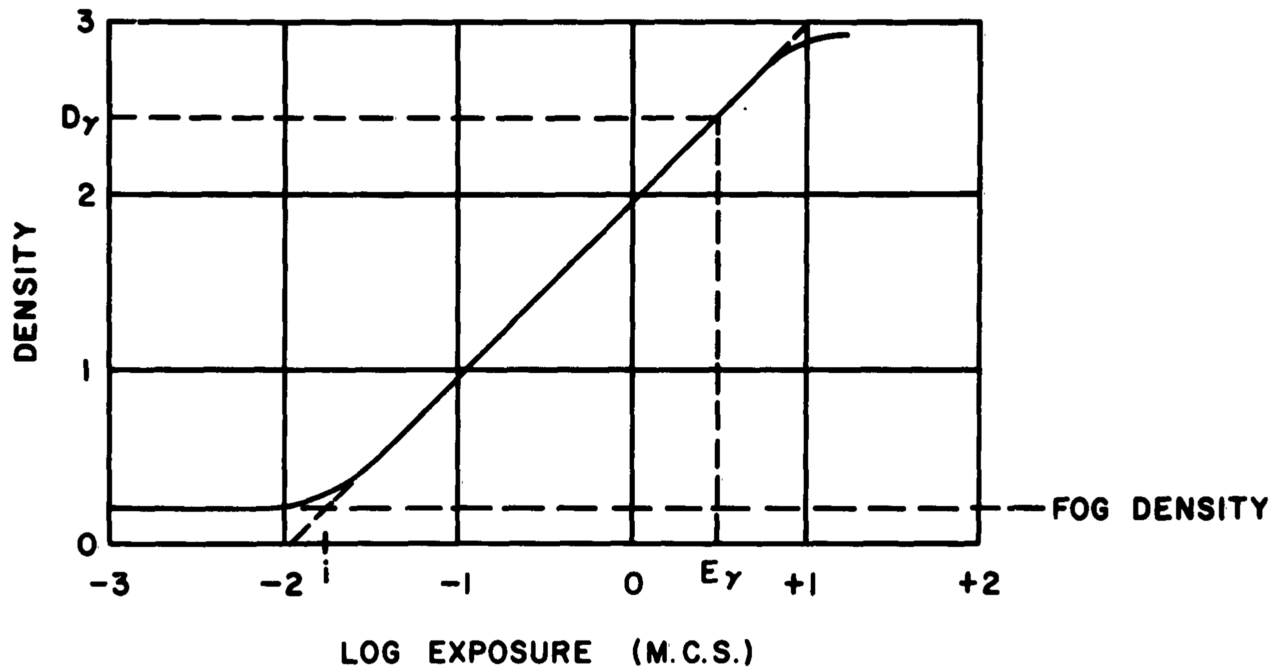
H AND D LOG E CURVES

The relationship between exposure and resulting film density is customarily described by characteristic curves obtained from exposure and development under standard conditions. These curves are usually plotted as density versus the common logarithm of exposure and are most commonly now referred to as D log E curves although the term "H and D curves" is often used. The latter appellation results from the work of Hurter and Driffield who were the first to employ this method of representation of film characteristics.

A typical D log E curve is shown in Figure 35. This figure is somewhat idealized to demonstrate the use of such curves and is not truly representative of any particular film. In actuality, the linear portion of the curve will deviate somewhat from linearity and the transition from the linear to the curved portion will be less clearly defined. Generally speaking, however, one can draw several useful conclusions from such a representation. Density is defined as the logarithm of the opacity or

$$D = \text{Log}\,\frac{1}{T}$$

where T is the transparency.



TYPICAL D LOG E CURVE

FIGURE 35

Since density is a measure of contrast, a proportional rendering will result if the exposure is confined to the linear portion of the characteristic curve. For example, a scene containing a brightness range of 10:1 would result in an exposure range of 10:1 or log 10 = 1 unit on the log E scale. If the linear slope were unity and the exposure range confined to the linear range, a density range of 1 would result with a consequently exact rendering of the scene brightness scale.

The intersection of the extension of the portion of the D log E curve with the horizontal line representing the fog level determines a value of exposure often referred to as the inertia i of the emulsion. *The slope of the linear portion of the curve is customarily designated γ and may be determined from

$$\gamma = \frac{D_r - D_{fog}}{\left[\operatorname{Log} E_r - \operatorname{Log} i\right]} \tag{58}$$

where the subscript indicates any corresponding pair D, log E which are related by the linear portion of the curve. The slope may naturally and usually more conveniently be measured by taking the ratio of any two corresponding differences on the straight line section of the curve.

*Other definitions are sometimes used.

In this portion of the D log E curve, the density and exposure are related by

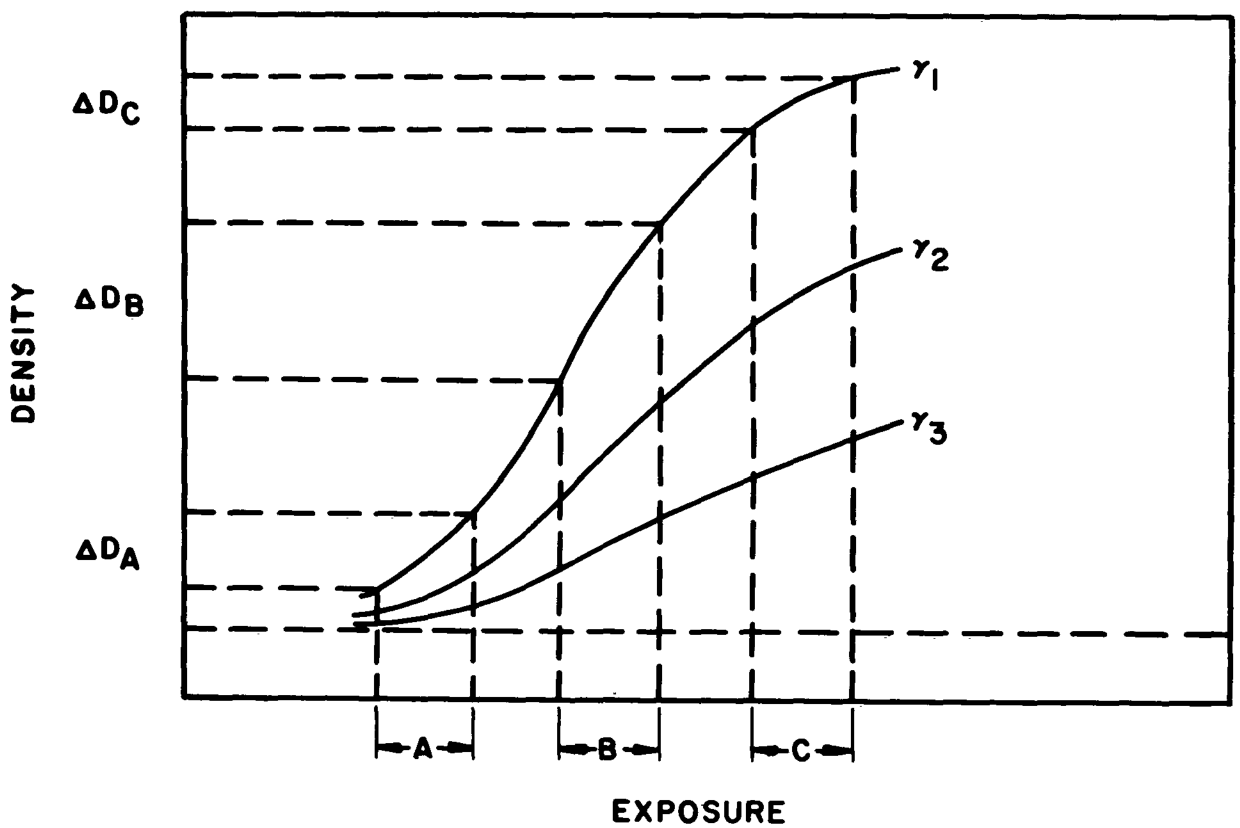
$$D = \gamma \left[\text{Log } E - \text{Log } i \right] + D_{\text{FOG}} \tag{59}$$

This expression indicates the value of a logarithmic representation and logarithmic differences aside from the resulting scale compression.

The value of γ obtained in practice is a function of the degree of development and varies with the development time, all other factors being the same. The exposure varies from point to point over the sensitive material, in ordinary cases, and γ is equal to the contrast ratio between image and subject as long as the exposure was confined to the linear portion of the D log E curve. If such is not the case, the contrast ratio is not constant over the entire subject brightness range. In the case of extremely low contrast scenes, development to a higher γ yields a reproduction of greater contrast than the original, and the reverse is true for development to a lower γ. The case of $\gamma = 1$ is equivalent to an exact rendering of the subject brightness distribution. Again, the above statements are predicated upon operating in the straight portion of the D log E curves. Figure 36 demonstrates the effect of exposure and development upon the resulting density range for a fixed exposure range. Note that the curve labeled γ_2 might correspond to $\gamma = 1$ for an exact reproduction of the object scene brightness. Development to γ_1 increases the contrast ratio and development to γ_3 lowers the ratio. The region marked "A" corresponds to underexposure, and that marked "C" to overexposure. The correct exposure, marked "B" is confined to the linear region of the curves. As can be seen from the curves, one cannot draw a general conclusion in regard to the use of development as a cure for exposure error. In some cases, particularly those involving low brightness range, a correction can be made. In the case of automatic exposure control being considered here, such techniques are beyond the scope or the fundamental problem.

We have seen that confinement of the exposure to the linear portion of the D log E curve results in proportional representation of the subject. The total range of the straight portion of the curve in log exposure units is referred to as the latitude of the emulsion. Since it is often difficult to determine the exact point of transition into the curve, measurement of latitude is not usually carried to extreme accuracy. The term is useful, however, in describing the exposure range over which density is proportional to log E.

The typical case is one wherein proportional representation is desired over a given range of subject brightness. Unfortunately, the range of subject brightness is amenable to ready measurement only under a few conditions. Such measurement might be made manually by means of an exposure meter of suitably restricted aperture.



EFFECT OF EXPOSURE AND DEVELOPMENT ON CHARACTERISTIC CURVES

FIGURE 36

In this case, there would be no need for automatic control. In the second case, a scanning exposure meter might be employed to measure both the maximum and minimum brightness levels within the camera field of view automatically, compute the geometric mean and establish the f setting. The latter method requires relatively sophisticated equipment. In the lower portion of the D log E curve, we are faced with low densities and a lowered gradient. At the high end, the gradient decreases and density levels become very high. The dynamic range of the film is, therefore, well represented by the emulsion latitude, as previously defined.

If the latitude be found, in a particular case, by the difference between an E_{max} and an E_{min}, then

$$L = \text{Log}\, E_{MAX} - \text{Log}\, E_{MIN} \tag{60}$$

in log E units. Since exposure is proportional to the brightness B, the value of L so arrived at represents the logarithm of the greatest range of B which can be accommodated by the emulsion and still yield proportional representation. If a value of B were available which represented the geometric mean of the subject maximum and minimum brightness levels, i.e.,

$$B_o = \sqrt{B_{MAX} B_{MIN}} \tag{61}$$

then the following ratios hold

$$\frac{B_o}{B_{MIN}} = \frac{B_{MAX}}{B_o} \tag{62}$$

and selection of a desired exposure on the basis of B_o insures that the log range of exposure above this level will be equal to the range below. Then if the desired exposure is taken as the center of the line representing the proportional section of the D log E curve, the brightness range of the subject will be applied to the dynamic range of the film in an optimum manner. Clearly, if the brightness range of the subject exceeds the proportional range of the film, then the density range cannot truly correspond to the brightness range under any circumstances.

It has been found, however, that satisfactory results can be obtained by extending slightly into the lower knee of the D log E curve.

Many emulsion samples have been subjected to sensitometric testing in the Data Corporation laboratories and D log E curves plotted for these samples. While these data will not be reproduced here, it will be stated that there is generally an appreciable variation from the idealized form of the curves described herein. This variation is not sufficient to render the idealized model greatly inaccurate for general discussion, and a smoothed version of the actual curve is quite sufficient for design purposes.

FILM SPEED

Film speed, or sensitivity, is proportional to the reciprocal of an exposure sufficient to yield a given result. Several methods of determining film speed are employed, although the American Standards Association procedure is now the most generally recognized and accepted method of determining and stating the speed of emulsions in this Country. The history of the measurement of film sensitivities indicates that any method which is readily applied, yields consistent results and is meaningful might be acceptable. The ASA speed determination certainly meets these requirements and has been reduced to a specific technique of measurement.

The fundamental objective of the ASA method is the determination of an exposure corresponding to the minimum usable density difference. The measurement itself has been established as the determination of the exposure E_o corresponding to a point on the D log E curve at which the gradient is 0.3 that of a straight line connecting log E_o and log E_o + 1.5. In symbolic form, the condition for the determination of E_o is

$$\left.\frac{\partial D(\operatorname{Log} E)}{\partial \operatorname{Log} E}\right|_{E=E_o} = 0.3\left[\frac{D_{E_o+1.5} - D_{E_o}}{1.5}\right] \tag{63}$$

where D (log E) is the characteristic function and the D_l refer to the density corresponding log E_o and log E_o + 1.5 exposure unit.

Other methods employed include the Weston determination, in which the desired value of E_o corresponds simply to $D = \gamma$ and the German Industrial Standard (DIN) method which determines E_o as the exposure equivalent to a density 0.1 above fog.

The ASA speed is given by

$$\text{ASA SPEED} = \frac{1}{E_o} \tag{64}$$

where E_o is determined by the ASA method and the Weston speed by

$$\text{WESTON SPEED} = \frac{4}{E_o} \tag{65}$$

where E_o for the Weston Method is found from the characteristic curve at the point

$$D(E_o) = \gamma \tag{66}$$

In all the preceding measurements, the film samples are exposed and processed according to certain exacting requirements in order that the results will be meaningful when comparisons are made between films of various ratings. The film speed is an indication of sensitivity and is a rating factor commonly available. The film speed, for best results under exacting circumstances, should be determined for samples of the film to be used. In this manner, variations due to ageing, storage conditions, etc. may be accounted for to the limit of the photographic process.

The present interest in film speed is based on the fact that the user ordinarily has available to him only the film speed rating of the film to be employed. In certain cases, this may not be so, and it is to be expected that consistently higher quality photography (from an engineering standpoint) is to be obtained if recent sensitometric data are available. If not, then the published film speed is based on a repeatable procedure rather than on a factor which may be used on a one-for-one basis in determining proper exposure. It is for this reason that the importance of empirical methods of calibration are stressed herein.

CHAPTER V

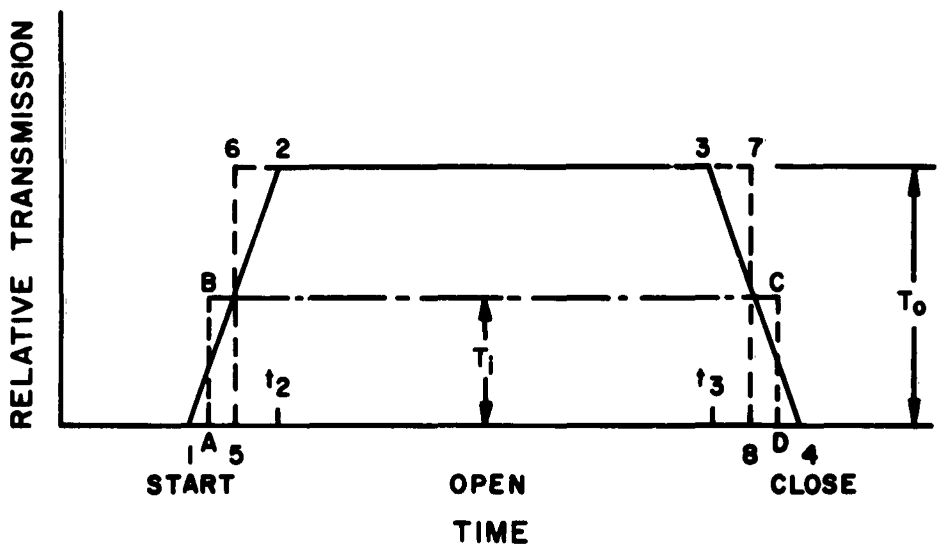
THE INDIVIDUAL TERM ANALYSIS OF THE AUTOMATIC

EXPOSURE EQUATION

Section 3. The "t" Term

Since exposure in the region where reciprocity holds is the product of illumination of the image by time, it is of interest to determine the effect of shutter performance. Two types of shutters will be considered on the basis of their effect upon the exposure equation. The shutter affects the exposure equation through the true effective exposure time and for this reason, it is extremely important that this time be known and constant for a given shutter speed marking.

The between-the-lens shutter is subject to the ordinary failing of mechical devices in being unable to execute the opening and closing cycle in zero time. The full cycle for a shutter of this type is, therefore, similar to that portrayed in Figure 37.



ROTARY SHUTTER CYCLE

FIGURE 37

At the time indicated as point 1 in Figure 37, the shutter begins the opening cycle. If the aperture is set at maximum, then the light transmission increases along line 1 - 2 until the fully opened position is reached. At the end of the fully opened cycle 2-3, the shutter returns to the fully closed position from point 3 to point 4. The area enclosed by the cycle 1-2-3-4 is identical to that encompassed by 5-6-7-8, and for this reason the time 5-8 is referred to as the effective open time of the shutter. As the aperture setting diminishes to the level B-C, the effective open time more nearly approaches the total open time 1-4. For near zero transmission, the two times approach equality. If then we assume the figure to be an isosceles trapezoid of altitude t_o, the ratio of effective open time to total open time as a function of t is given for a particular total open time by

$$\frac{t_{eo}}{t_{to}} = \left[1 - \frac{(t_2 - t_1) + (t_4 - t_3)}{2(t_4 - t_1)}\right] \tag{67}$$

and one can readily perceive that a single point calibration is insufficient to cover a wide range of aperture settings. As the speed of shutter operation increases, the problem is repeated. Note in the equation above that as the exposure time diminishes, the numerator of the fraction on the right hand side approaches unity and the ratio of effective to total open time approaches 1/2. It is, therefore, apparent that shutter speed, as employed in the automatic exposure control equation, should be the effective open time, regardless of shutter calibration. Fortunately, many uses do not require the combination of high shutter speed and small aperture which yields the greatest deviation in shutter efficiency. In other applications, however, this possibility definitely exists and must be accounted for. At slow shutter speeds, the change in efficiency over a range of aperture settings is not great, but may be so at the higher speeds.

The focal plane shutter operates on the principle of the movement of a slit across the film plane rather than upon the moving blade principle of the between-the-lens shutter just discussed. Therefore, the focal plane shutter is customarily calibrated in terms of effective open time. If the width of the slit were constant and the speed of movement did not vary as the slit moves across the focal plane, the efficiency of the shutter would be very high. In practice, however, one finds that there is some variation in exposure over the travel of the slit due to change in velocity of the slit. Some reduction in efficiency is also observed as a function of width of the slit, and the distance between the slit and the film. Since the "opening time" (analogous to that of the blade shutter) is the time required for the slit to traverse the cone of light formed by the lens, one can relate the efficiency to the factors involved by

$$E = \frac{S}{S + \frac{d}{f}} \tag{68}$$

where S is the width of the slit, d the distance between the slit and the focal plane, and f the f-number of the lens. The limiting slit width can be computed from

$$S_{MIN} = \frac{d}{f} \tag{69}$$

since below this value the slit will contribute to a reduced effective aperture.

Since the undesired acceleration of the slit varies with speed, effective open times are computed on the basis of the average between maximum and minimum aperture at a given speed. The true exposure time then varies about the average so arrived at over various aperture settings. Temperature may also appreciably affect the operation of any mechanical shutter when operation over wide temperature range is required. This effect is variable with design and must be determined experimentally.

In addition to the above reasonably static considerations, the possibility exists that shutter parameters may vary with the operating history of the camera. The environment, maintenance, mechanical wear, etc., are all involved and relatively unpredictable. Again, such variables are usually outside the loop in automatic exposure control systems and must be accounted for in calibration and operational procedures. Probably the best technique available for employment of such devices would be the calibration of lens, shutter and diaphragm as a unit.

CHAPTER V

THE INDIVIDUAL TERM ANALYSIS OF THE AUTOMATIC EXPOSURE EQUATION

Section 4. The "f" Term

For constant brightness, the exposure equation reduces to

$$E = \frac{Kt}{f^2} \tag{70}$$

and one can readily appreciate the efficacy of aperture adjustment in controlling exposure. In some systems the exposure time is adjusted over certain ranges to control exposure, but the ever present interrelationship of parameters tends to emphasize the position of aperture as the controlling variable.

The usual method of exposure control is by the physical change of aperture through the employment of a mechanical light restriction. In simple cameras, this restriction may consist of a selection of holes of varying size, but the iris diaphragm is most commonly used in conventional photography. The iris diaphragm consists of a number of overlapping leaves which may be opened or closed to change the size of the aperture. The diaphragm, for best results, should be calibrated with the lens to provide the greatest degree of precision in relative transmission of light. Systems so calibrated are often marked in T numbers rather than f numbers to indicate that the calibration refers to total transmission calibration.

One readily useable feature of the iris diaphragm is found in aperture controls utilizing direct coupling of sensor and primary lens diaphragms. In this case absolute foreknowledge of lens transmission coefficients is unnecessary due to the self-correcting nature of the system. If such is not the case, and the feedback is electrically accomplished as a function of the rotational position of the diaphragm control ring, then the relationship between rotation and transmission of light must be known to a degree of accuracy consistent with other requirements. In this case, the iris diaphragm is somewhat subject to the mechanical problem of the shutter in that repeatability is required after nominal performance has been established. Generally speaking, maximum resolution is attained at large aperture and fast shutter speed when viewing low contrast targets with motion involved. For this reason, the trend in aerial photography has been toward large apertures and reduced exposure time. In general use, however, apertures may vary considerably.

In the exploitation of the iris diaphragm, one must consider the mechanical limitations of the device. An iris diaphragm usually exhibits an appreciable inertia which generates a need for appreciable torque from the drive motor. On the other hand, many such diaphragms are not mechanically sound enough to permit a sudden stop at the end of travel when the stop is to be repeated a number of times. For this reason, an electric stop may be necessary in addition to the need for care in establishing the maximum driving speed.

CHAPTER VI

DESIGN CONSIDERATIONS

Section 1. General Considerations

In earlier sections, the automatic exposure control equation has been developed and various terms discussed at some length. In the present chapter, an attempt will be made to reduce the earlier material to a set of general design guidelines and to formulate requirements for the evaluation of such systems. One should first realize that it is fundamentally unsound to regard automatic exposure control as a completely closed-loop process. Ideally, one might consider a perfect closed-loop photographic process to consist of a system similar to that shown in Figure 38. Certainly, several features of this system are impractical and cannot be economically or reasonably accomplished. In a reasonably constituted system, several features must be incorporated outside the control loop. Since this is so, these features must be controlled to a level of accuracy consistent with the goals of the entire system. The block diagram of a practical system is shown in Figure 39. Note that by necessity many of the essential features must remain outside the system proper. Establishment of film parameters based on standard techniques is accepted as precomputed information. In the example shown, the light transmission factor is also externally entered although, as we have pointed out earlier, this entry can be better accommodated by other means. The example does indicate, however, that the fundamental principal of automatic exposure control is considerably limited in scope and the operation of such a system depends heavily upon the correctness of precomputed data.

The automatic exposure equation may be written

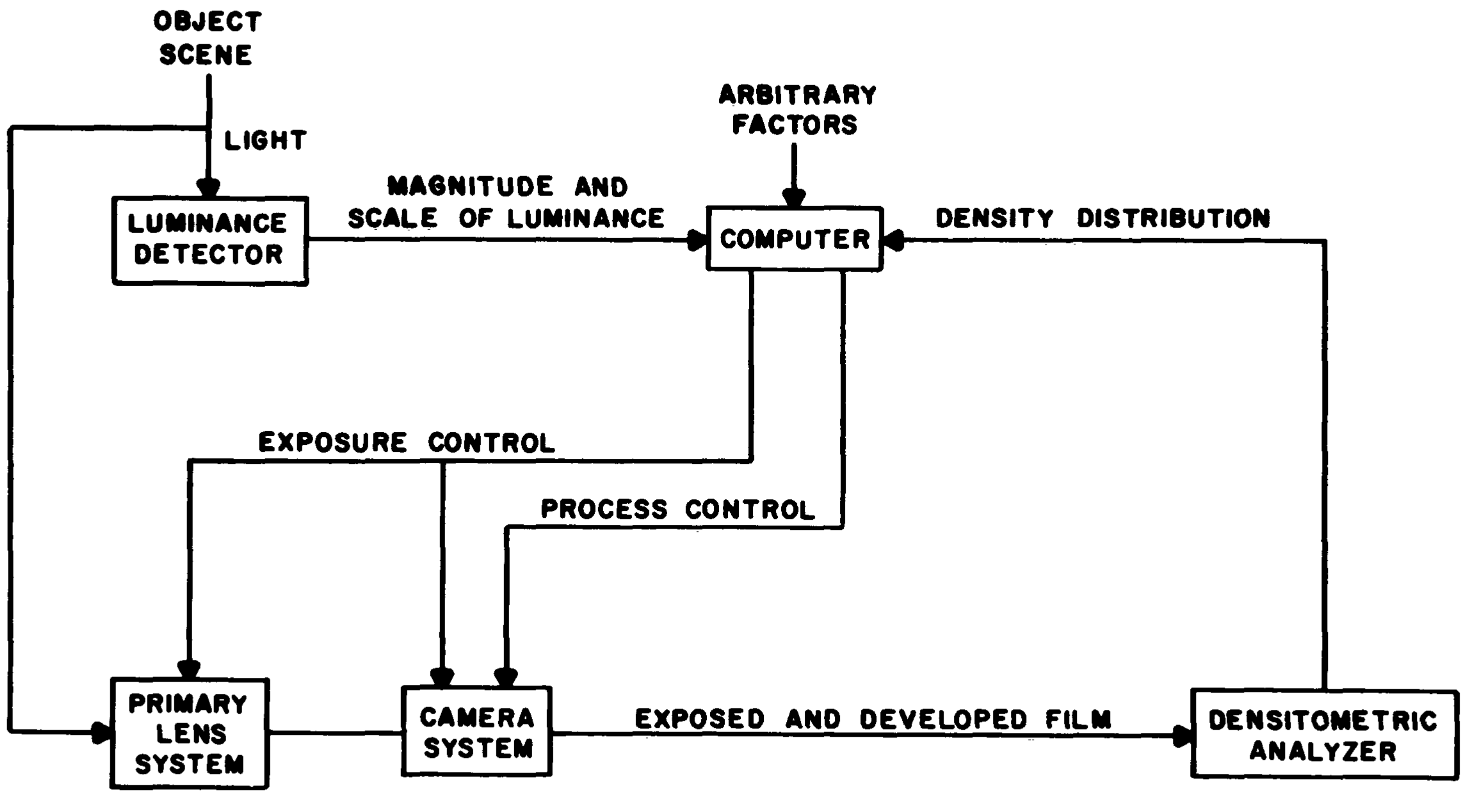
$$f^2 = K B t S_a \tag{71}$$

but the method of error analysis depends upon the physical configuration of the system. Two cases will be considered, and although the equations are essentially identical, the method of effecting control requires a different form of analysis. The two types of systems to be considered are

Case 1. The system is described by the equation above. Sensing and primary lenses are the same or identical and the aperture is driven until the average output of the sensor is equated to a precomputed value.

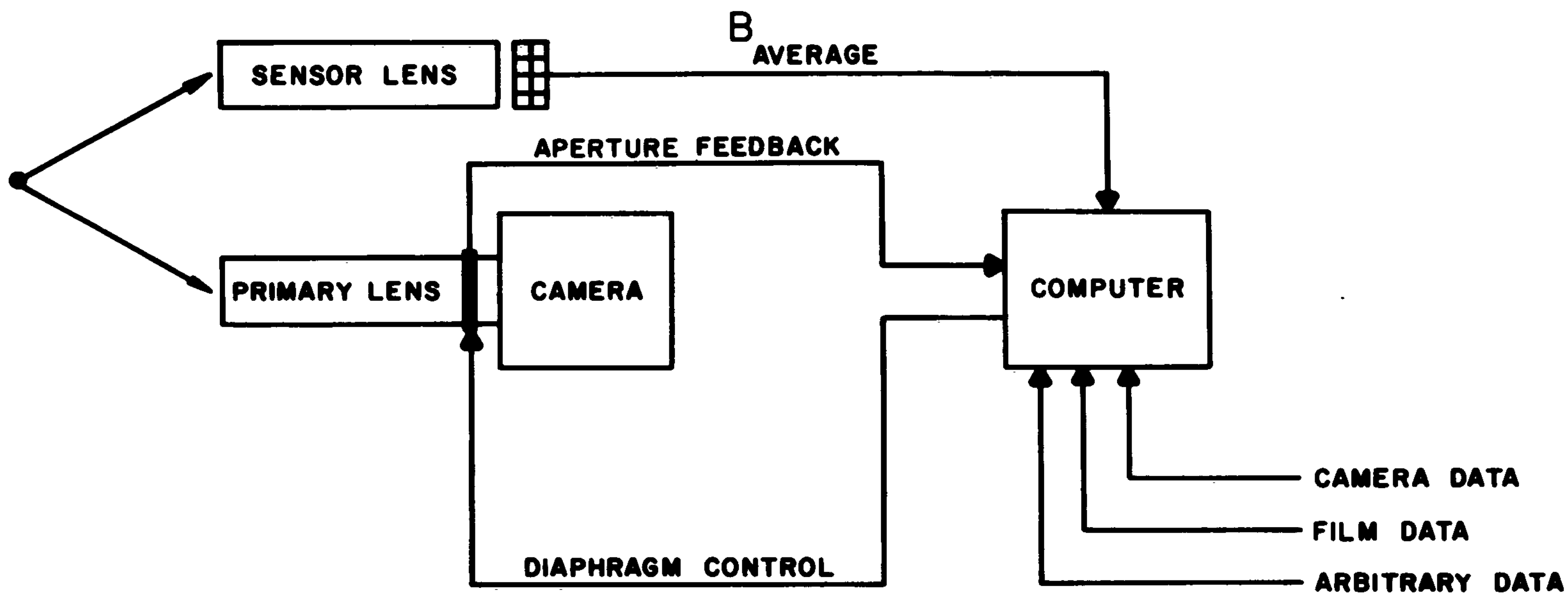
Case 2 The system implicitly operates by the equation

$$E_{REF} = \frac{K' B T t}{f^2}$$



GENERALIZED "IDEAL" AUTOMATIC PHOTOGRAPHIC SYSTEM

FIGURE 38



READILY REALIZABLE SYSTEM

FIGURE 39

and an electrical position feedback is used to monitor the position of the diaphragm control ring. The value of E_{ref} is precomputed as are T and f (as a function of rotation).

In Case 1 the system is self-compensating insofar as the lens aperture combination is concerned and the aperture will change until the equation is satisfied. In the second case, all variables must be established in advance and must, therefore, be considered in error analysis. In both cases, B is the independent variable and cannot be controlled. Also, a finite range of f exists in both cases.

From Eq. (1) Chapter I by differentiation and some manipulation of terms,

$$2f^2\frac{df}{f} = KBtS_a\left[\frac{dK}{K} + \frac{dB}{B} + \frac{dt}{t} + \frac{dS_a}{S_a}\right]$$

OR

$$\frac{df}{f} = \frac{1}{2}\left[\frac{dK}{K} + \frac{dB}{B} + \frac{dt}{t} + \frac{dS_a}{S_a}\right]$$

Then if we assume the uncertainty in each quantity to be independent, we can estimate the uncertainty in f as

$$\overline{\Delta f}^2 = \frac{1}{4}\left[\overline{\Delta K}^2 + \overline{\Delta B}^2 + \overline{\Delta t}^2 + \overline{\Delta S_a}^2\right] \tag{72}$$

where now the $\overline{\Delta f}$ refers to a fractional error. We assume now that the error is unaffected by the mechanical means of effecting balance on the basis of the assumption that this will not be a limiting factor. At the risk of repetition, again note that the error so derived refers only to the degree of attaining the desired value of f based on the system inputs. No account is taken, for example, of the disparity between average brightness and the geometric mean of maximum and minimum brightness since it is mandatory in this type of system that such relationships be empirically determined as part of the constant K.

It is perhaps easier to give physical substance to Eq. (72) if we recall that

$$f = \frac{q}{D}$$

where q is the lens focal length and D the aperture diameter. Then

$$|\overline{\Delta f}| = |\Delta D|$$

since q may be considered negligible. Referring now to Eq. (1), we see that an accuracy of about 1/4 f stop can be attained if the uncertainty in each of the other variables does not exceed 10%. At first glance, this requirement does not seem particularly pressing due to the amenability of some of the factors to calibration. In face the entire system is amenable to calibration under the design philosophy under discussion. The error term of Eq. (72), however, refers to the uncertainty involved. Let us, therefore, examine some of the possibilities for uncertainty:

K:	Calibration error due to nonstandard conditions or measurement error
	Improper transformation factors
B:	Presence of nonimage forming light
	Improper spectral characteristics
	Temperature sensitivity
	Improper field of view
	Improper calibration
t:	Mechanical wear after calibration
	Temperature change
	Improper calibration
S_a	Ageing of film due to excessive or improper storage
	Excessive latitude in sensitometric measurements
	Incorrect reporting of characteristics

In this type of system inconsistencies in T and f are not necessary to analysis, providing these variations are small and the two lenses are reasonably matched.

Of the above sources of error, we may consider most to be amenable to correction by:

1. Use of consistent and standard practices in measurement and calibration
2. Reasonable environmental control, where necessary
3. Periodic calibration checks
4. Adequate testing of film samples within a reasonable period of the anticipated use

The necessity for such practices may be exemplified by the following instances of reported parameter change in severe and uncontrolled circumstances:

S_a : 60%

t : 20%

On the other hand the wide emulsion latitude of many types of films renders the 1/4 f stop control unnecessary. If this requirement can be met, however, the system will perform satisfactorily under any circumstances wherein the range of luminance of the object can be accommodated by the film on each side of the reference exposure. This is true for color as well as black and white, assuming proper calibration of the system. A simplified diagram of a system of the type just described is shown in Figure 40.

The situation is somewhat different in Case 2, inasmuch as the end is approached in a manner as described in Figure 41. In this case E_{ref} could easily be replaced by S_a with a corresponding change in K, but the present nomenclature will be retained as an aid in visualizing the type of system involved. Let us now examine the following equation:

$$E_{REF} = \frac{K' B t T}{f^2} \tag{73}$$

T also can be absorbed into another constant, but note that such a procedure leaves no ready means of correcting for filter factors or known transmission irregularities. The preferable solution would be to absorb T into the square law pot used for feeding back the f stop. In this case, the external potentiometer correction for filter factors would still be required but the pot would be calibrated in t rather than f factors. Other changes in transmission characteristics could only be accommodated by a change of potentiometer.

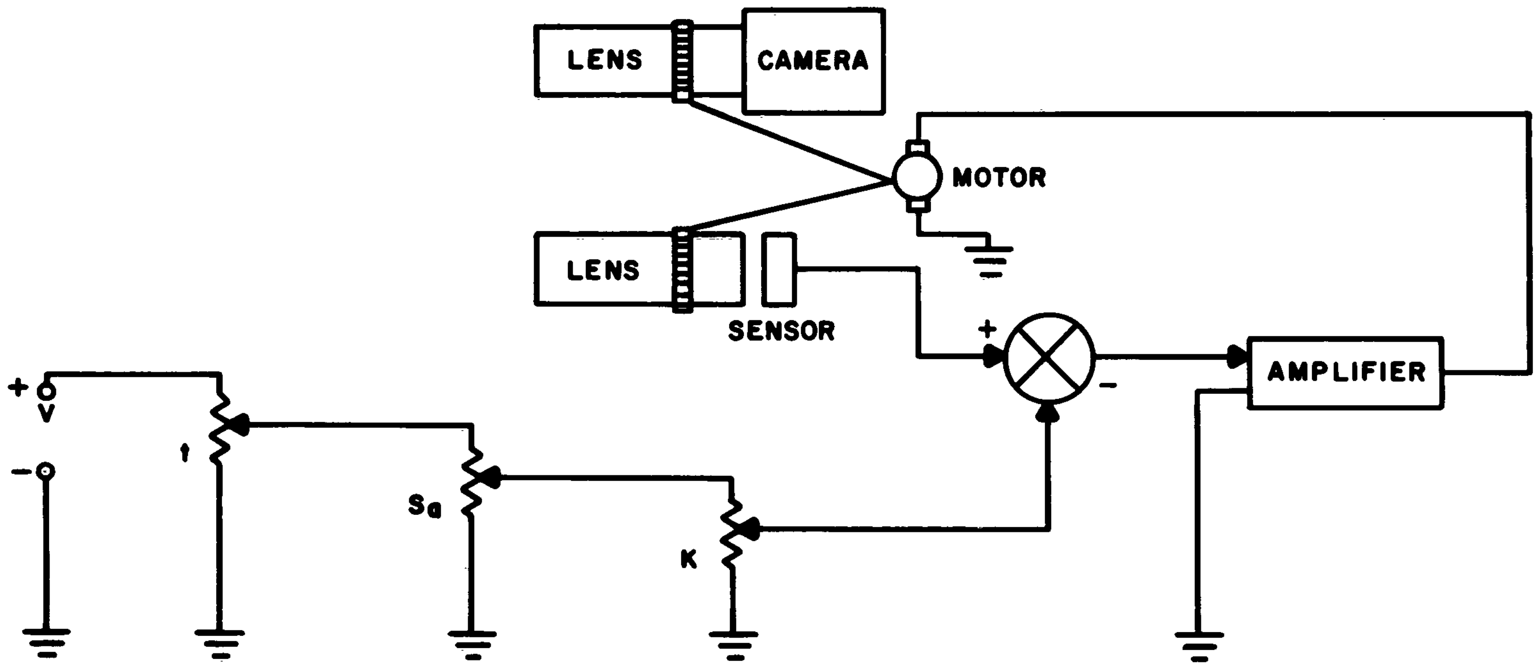
Again differentiating and collecting terms as before, we have

$$\overline{\Delta E_{REF}^2} = \overline{\Delta K^2} + \overline{\Delta B^2} + \overline{\Delta t^2} + 4(\overline{\Delta f^2}) \tag{74}$$

One can now observe a modest fundamental difference between the two approaches. The difference arises from two factors:

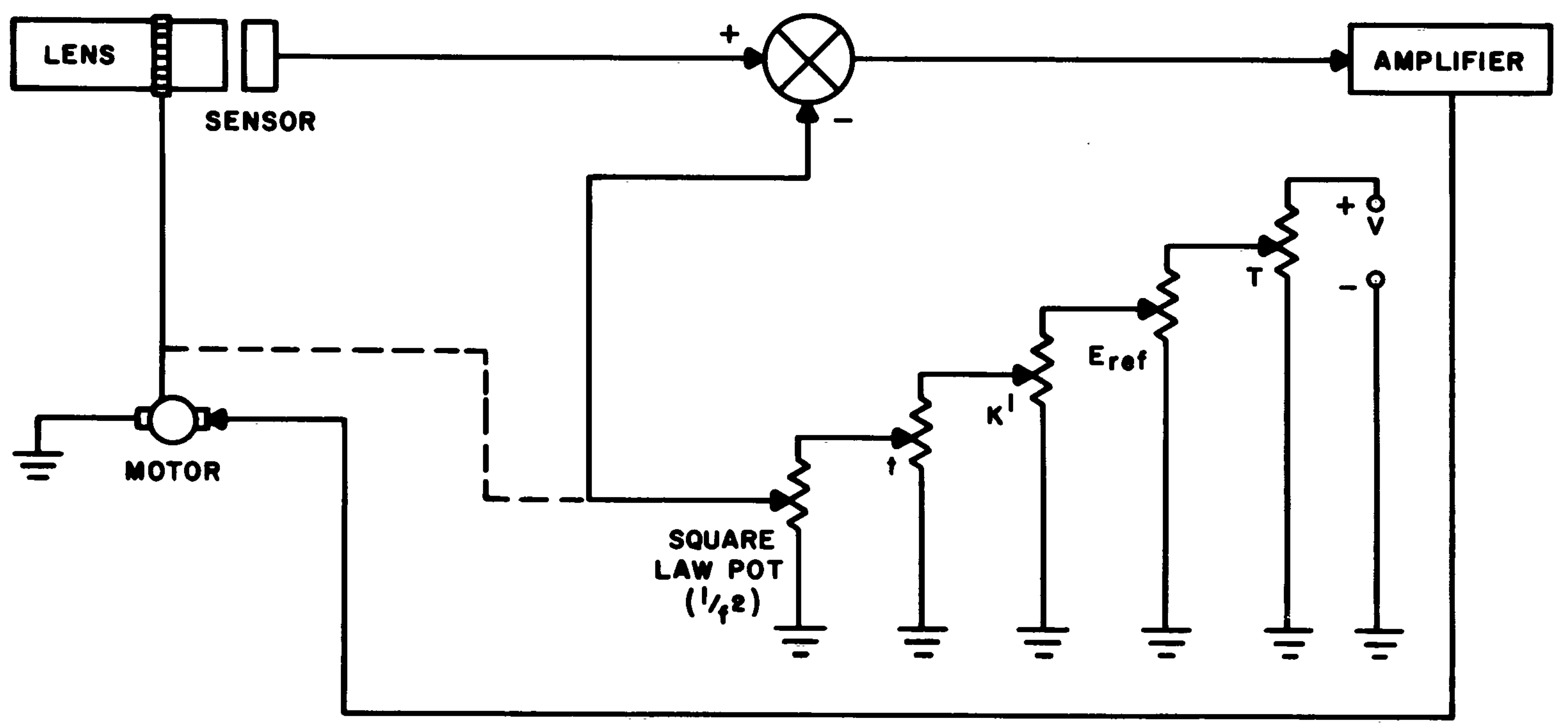
1. Case 1 is optically self-compensating to a degree.

2. The use of the potentiometer, if not exactly matched to the lens t factor, gives rise to a secondary source of error. T, if separately compensated for, may not necessarily be constant over all aperture settings.



CASE I, EXPOSURE CONTROL SYSTEM

FIGURE 40



CASE II, EXPOSURE CONTROL SYSTEM

FIGURE 41

Otherwise the two systems are mathematically equivalent and subject to the same restrictions. The optical self-compensation of the system of Case 1 is only attainable by the use of identical filters on each lens, when a filter is employed. If the spectral characteristics of film and sensor are reasonably well matched, then this advantage is attained over a wide range of conditions.

The basic requirements of the servo system present an unusual set of design criteria to the servo designer. Probably the most stringent requirements are those of economy and size. The time response, overshoot, damping and accuracy requirements, relatively speaking, are easily attained. For example, the following specifications of the KS - 27A System are:

Maximum Time Response	4 seconds
Maximum Damping Time	1 second
Maximum Permissible Overshoot	30%

The KS-27A specification also requires that the system shall correct itself when the brightness level changes by a factor of two.

Figures 42 and 43 show two types of closed-loop systems that are utilized to control the aperture. The former Figure shows a system that incorporates an electric feedback signal whereas the latter Figure shows a system incorporating a mechanical feedback signal. These systems are either "Proportional error systems" or nonlinear systems (such as "on-off" relay control systems).

Figure 44 is a block diagram of a proportional error "positioning" servo system where R_o is a potentiometer mounted on the output shaft. When the voltage across the slider arm of R_o (and ground) is equal to the input signal then the error signal at the input of the amplifier is zero. Likewise the output of the amplifier is zero and the output shaft remains the same position. When the input V_i is changed, an error voltage (V_i - V_f) will exist at the input of the amplifier. This in turn is amplified and the output energy is supplied as a torque to the output shaft. The amount of torque applied to the shaft is proportional to the error signal of the amplifier.

Figure 45 is a block diagram of a typical "ON-OFF" Control System. From this diagram it can be seen that when the position of the slide arm of the potentiometer is positioned so that the voltage across the arm of the slider is different from the input signal, there is an error signal. When the error signal exceeds a given magnitude, the relay will close. Energy will then be supplied to the output shaft by the motor. Note that the torque applied to the output shaft is not proportional to the error signal but is a constant value independent of the amplitudes of the error signal as long as its magnitude is greater than the level required to actuate the relay. It is of interest to note the system of Figure 45 possesses characteristics which are different from those of the system shown in Figure 44.

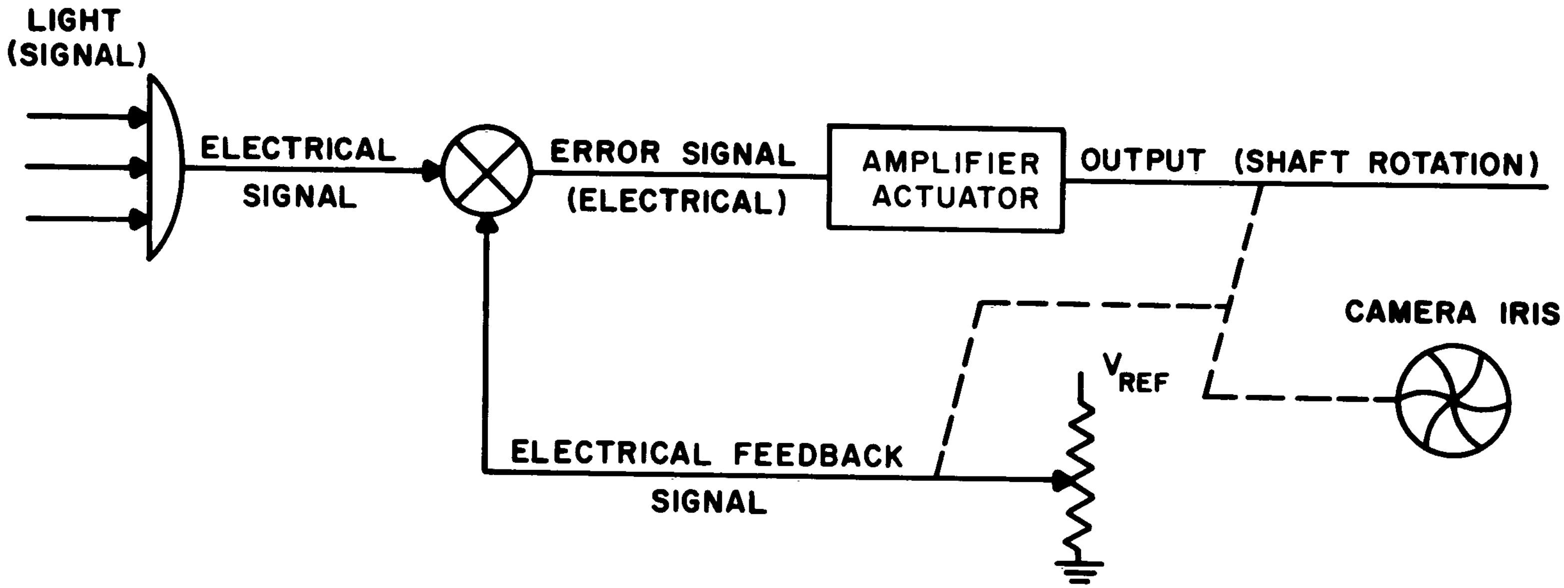
They are:

1. Limit Cycle

2. Dead Zone

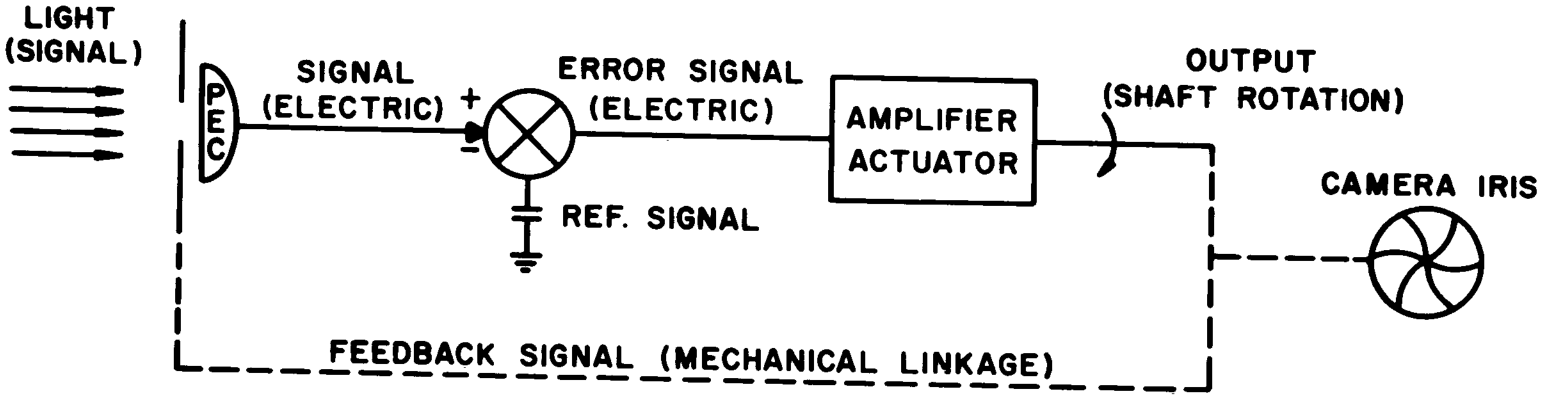
3. Time Delay

Several other characteristics may also occur in any nonlinear servo system. They are saturation, coulomb friction and backlash. These characteristics are also encountered during the testing and evaluation of the various exposure control systems.



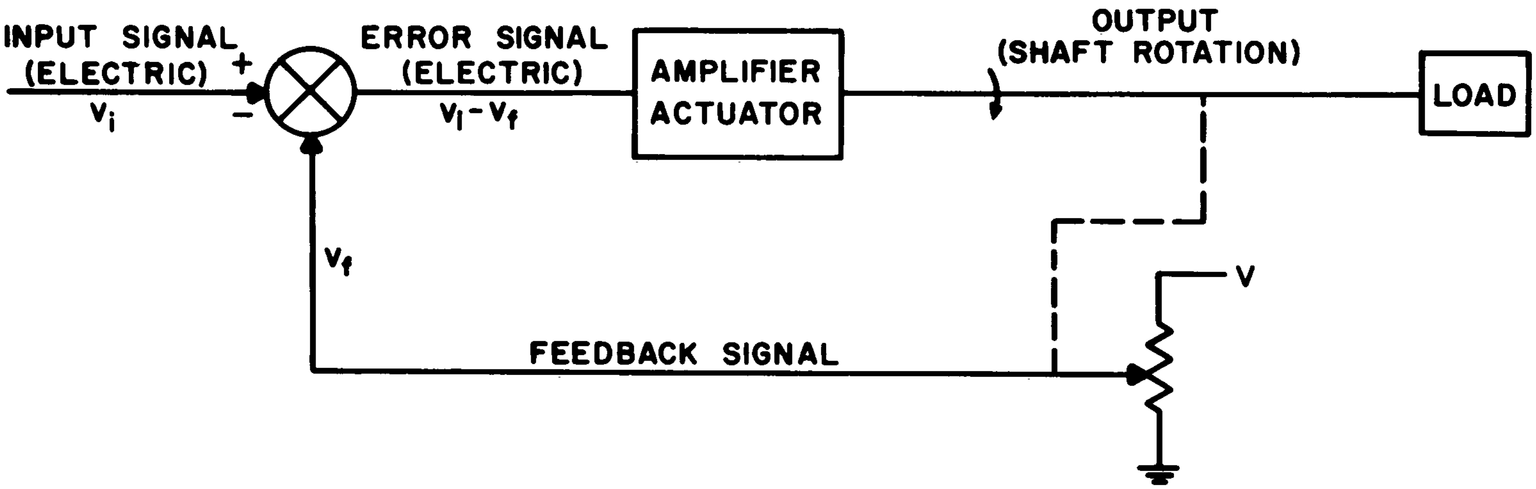
AEC SYSTEM WITH ELECTRICAL FEEDBACK

FIGURE 42



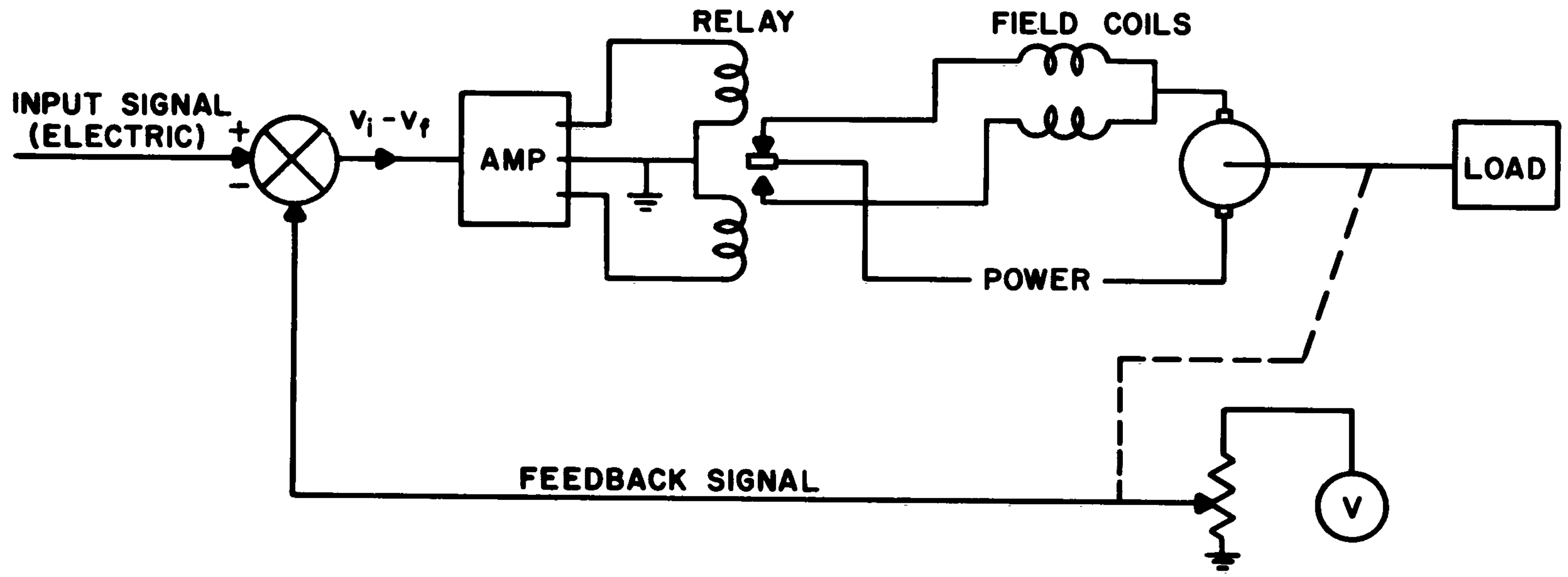
AEC SYSTEM WITH MECHANICAL FEEDBACK

FIGURE 43



PROPORTIONAL ERROR SERVO TYPE SYSTEM

FIGURE 44



"ON-OFF" TYPE AEC SYSTEM

FIGURE 45

CHAPTER VI

DESIGN CONSIDERATIONS

Section 2. Alternate Approaches

All possible methods of attaining the desired end cannot be discussed in detail, but some remarks will be made in regard to a few. In many applications it is known in advance that the scene contrast will be quite low. For example, in aerial photography terrain contrast rarely varies over a range greater than 10:1 and in some cases may not exceed 2:1. Films, on the other hand, might have a substantially linear range of over 300:1. If such a set of conditions is known, then certain simplifying steps may be taken. A range of brightness of 10:1 corresponds to a log exposure variation of ± 0.5 log E unit about a desired point. (In some applications increased resolution can be obtained by operating near the lower toe of the D log E curve, but in the present example it will be assumed that this is not a consideration). If the substantially linear range of the film is $\pm N/2$ log units about a reference point E_o then proportional representation can be obtained as long as

$$E \geq E_o - \frac{N}{2} + \frac{1}{2} N_c \tag{74}$$

$$E \leq E_o + \frac{N}{2} - \frac{1}{2} N_c$$

where:

E_o is the geometric mean of the extremes of proportional representation in log E units.

$N/2$ is half the emulsion linear dynamic range in log E units.

$\frac{Nc}{2}$ is half the scene contrast range in log units

E is the actual exposure in log units

Then the total available acceptable range of E becomes

$$\begin{aligned} \partial E &= E_{MAX} - E_{MIN} \\ &= \frac{1}{2} N - \frac{1}{2} N_c + \frac{1}{2} N - \frac{1}{2} N_c \qquad (75) \\ \partial E &= N - N_c \end{aligned}$$

Then, assuming an N of 2.5 log E units and an N_c of 1 unit,

$$\partial E = 2.5 - 1 = 1.5$$

and it can readily be seen that highly accurate control is not required, and ± 0.75 log E unit will result in an acceptable representation. Then assuming all error due only to f,

$$\frac{E_1}{E_2} = \left(\frac{f_2}{f_1}\right)^2 \tag{76}$$

and

$$\operatorname{Log} E_1 - \operatorname{Log} E_2 = 2 \operatorname{Log}\left(\frac{f_2}{f_1}\right)$$

$$0.75 = 2 \operatorname{Log}\left(\frac{f_2}{f_1}\right)$$

$$\frac{f_2}{f_1} = 2.4$$

Now let us consider a situation wherein the available stops are

f = 1.4, 2, 2.8, 4.0, 5.6, 8, 11, 16, 22

and it is desired that a simple system be used. Then if reference light levels are chosen for a given film characteristic and exposure time, we can choose these levels to produce a set of f numbers, all of which will be within the film tolerance of the correct value. For example, we can choose three levels of average light. Take the reference light levels in such a manner that

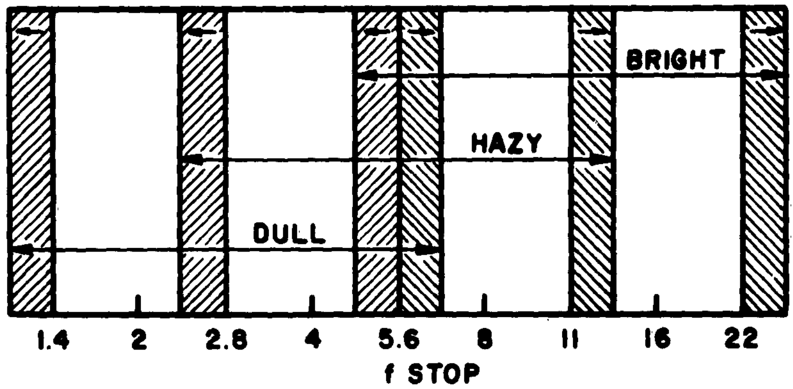
Level 1 (Bright)----------- f/11

Level 2 (Hazy)------------ f/5.6

Level 3 (Dull)------------- f/2.8

Note now that this system allows coverage of the entire range of adjustment, with an appreciable safety factor at each setting so that the chosen ranges overlap by more than one stop, as shown in Figure 46. The safety factor is shown by the shaded areas for the direction of change shown by the small arrows. It is seen that appreciable range overlap occurs. The advantage of such an overlap, of course, is that the system need make only an approximate judgement regarding the brightness level at which it is required to make an aperture change. The exact f number ranges will depend upon the situation, and the above are quoted only as examples for a hypothetical situation.

Other techniques which have been employed include the use of variable neutral density filters rotated in front of the lens rather than a diaphragm control.



EXAMPLE OF THREE STOP EXPOSURE CONTROL

FIGURE 46

Also, systems have been constructed utilizing a sensor within the camera or lens system so that the primary lens may be utilized for a dual purpose. This latter method may be applied in several ways, including:

a. Photoelectric sensors mounted near the image plane to utilize light not required in the formation of the image.

b. Use of a polished front shutter surface to reflect light into a sensor during the shutter closed period.

c. Use of a photoelectric sensor mounted on the front surface of the shutter. Two other approaches are described in Chapter V and that material will not be repeated in the present section. There are unique advantages and disadvantages involved in each of these techniques. The fundamental properties and problems of automatic exposure control remain the same.

CHAPTER VI

DESIGN CONSIDERATIONS

Section 3. Special Consideration in Air-to-Air Applications

Air-to-Air photography, such as is employed in aerial gunnery or rocketry, presents one of the most severe environments for automatic exposure control. Since the object is the photographing of a target against a sky background, several characteristics of the problem render proper exposure control very different. These factors include:

1. Variable solid angle subtended at the camera by the relatively small target due to range variation.

2. Unknown and variable aspect of camera and target with respect to the sun.

3. The lighting uncertainties created by the presence of clouds and reflecting haze layers.

4. Flexibility requirement imposed by the not uncommon need to utilize the camera as an air-to-ground strike recording camera.

5. Variable color temperature of the sky.

Factors (4) and (5) are relatively easily accommodated by careful design, but specialized techniques are sometimes required in reducing the effect of the remaining three. The target is ordinarily relatively small in respect to the angle of acceptance of the lenses used. Ideally, the system will respond to the brightness of the target rather than that of the environment. Due to the need for a reasonable angular coverage, however, it is not feasible to over-restrict the acceptance angle. For this reason, some method of deducing target brightness is indicated.

One method which has been used is similar to that mentioned earlier. The angular acceptance area is scanned mechanically or electronically for brightness distribution. The limitations of such a method are fairly obvious since it is not readily apparent that the target will be either the brightest or the darkest element of the scene viewed, and it is further not apparent that the total range of brightness observed can always be accommodated. A method which has been devised to simulate the brightness of the target is described in Reference 3-1. This technique makes use of the fact that air-to-air photography is employed only when the camera and target are in line and in approximately the same attitude with respect to the sun. A sensor is mounted on the aircraft in such a manner that the light received by the sensor is that reflected from either an aluminum plate especially mounted or from the aircraft itself. Then if specular reflection is not controlling (this would occur in a relatively few sets of circumstances) the brightness observed approximates that of the target aircraft. The sensor output may be used to control the f/stop or the shutter open time or both as desired.

The color temperature of the sky is observed to vary with time of day, time of year, weather and local conditions. The brightness of the sky is also affected by these factors. While a true standard is relatively meaningless in view of such variation, it is often assumed for design purposes that performance is to be evaluated at a color temperature of 5500° K at brightness levels to 10,000 foot-lamberts. It may also be of interest to estimate the illumination of a sensor for a given set of conditions, when the entire solid acceptance angle of the sensor is filled with a sky background of uniform brightness. By definition,

$$\mathcal{E} = B\omega \tag{77}$$

where

$\mathcal{E}$ is the illumination on the surface of the photosensor

B is the brightness of the sky

ω is the solid angle from which light is accepted by the sensor

The acceptance angle of the sensor is assumed to be equal to some value B in both azimuth and elevation. Then in order to determine the solid angle from which light is accepted, the area observed by the sensor on the surface of a sphere of arbitrary radius r is determined. From spherical geometry, refering to Figure 47,

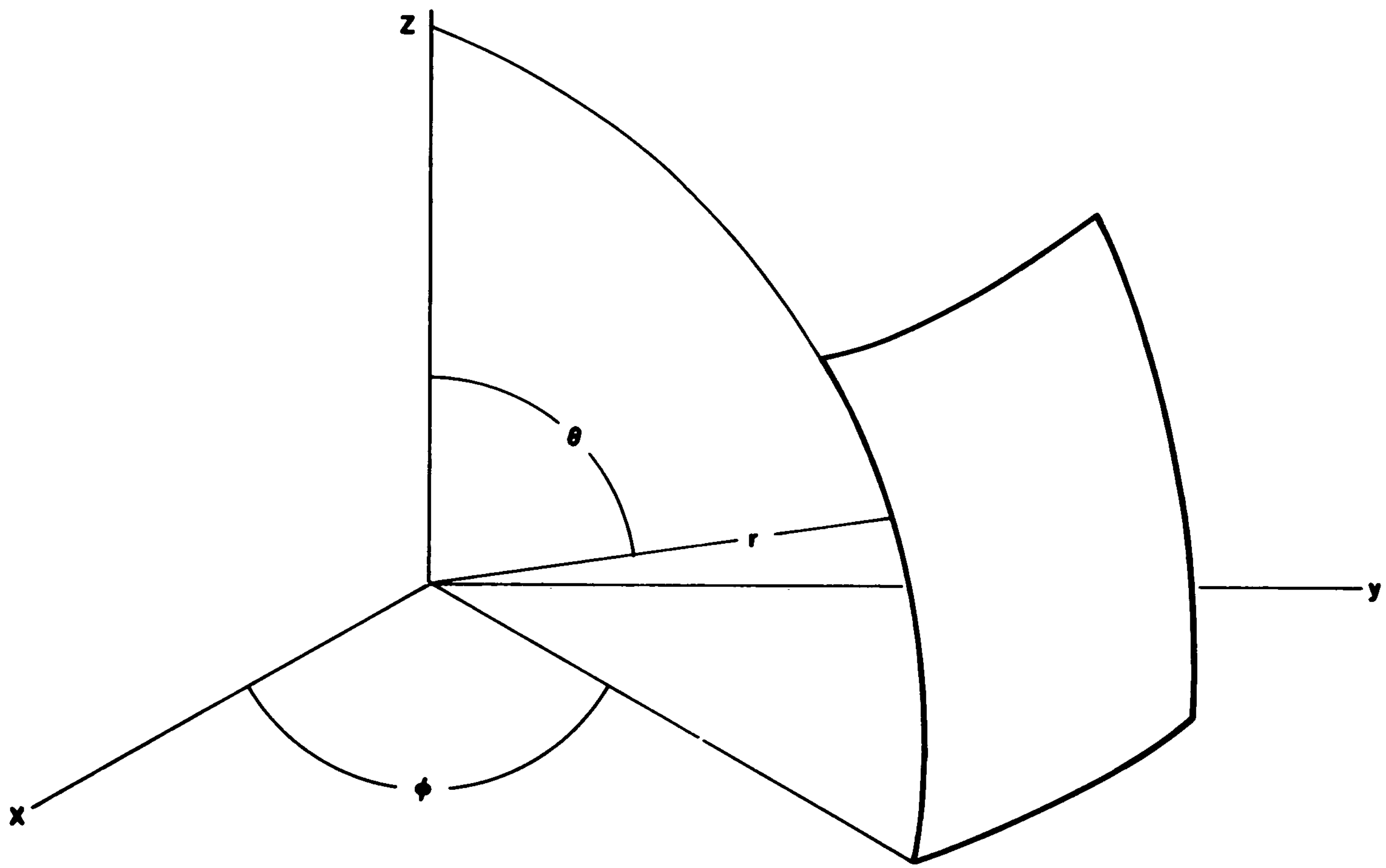
$$dA = r^2 \sin\theta \, d\theta \, d\phi$$

and

$$A = \int_{\frac{\pi}{2}-\frac{B}{2}}^{\frac{\pi}{2}+\frac{B}{2}} \int_{\frac{\pi}{2}-\frac{B}{2}}^{\frac{\pi}{2}+\frac{B}{2}} r^2 \sin\theta \, d\theta \, d\phi \tag{78}$$

and

$$A = r^2 \left[2B \sin \frac{B}{2} \right]$$



CALCULATION OF SENSOR ILLUMINATION DUE TO SKY BRIGHTNESS
FIGURE 47

The solid angle ω ,therefore, is

$$\omega = \frac{A}{r^2} = 2B \sin \frac{B}{2} \tag{79}$$

For $B = 30^\circ$ (a common value corresponding to $B/2 = 15^\circ$),

$$\begin{aligned} \omega &= 2(0.5236)(0.2588) \\ \omega &\cong 0.27 \text{ STERADIANS} \end{aligned} \tag{80}$$

If then one uses a sky brightness of 10,000 foot-lamberts, recalling that one foot-lambert is equivalent to π candles per square foot, the illuminance of the sensor due to sky brightness is:

$$\mathcal{E} = \frac{10{,}000}{\pi} \; 0.27 = 860 \text{ LUMENS}/Ft^2 \tag{81}$$

In applications where such a wide range of brightness uncertainty may be encountered, it often becomes desirable to possess the ability to vary both shutter open time and iris setting. In a camera such as the AN-N-6, the following limits of the variables apply:

$$\begin{aligned} 3.5 &\leq f \leq 16 \\ 0.005 &\leq t \leq 0.025 \end{aligned} \tag{82}$$

The maximum exposure condition corresponds to maximum t and minimum f, and the reverse is true for minimum exposure. The range of brightness which can be accommodated for constant exposure by varying f only is clearly

$$\left(\frac{f_{MAX}}{f_{MIN}}\right)^2 = \left(\frac{16}{3.5}\right)^2 = 20.8:1 \tag{83}$$

If both t and f are variable, however, the range becomes

$$\frac{\frac{0.025}{(3.5)^2}}{\frac{0.005}{(16)^2}} = 20.8 \times 5 = 104:1 \tag{84}$$

exclusive of the tolerance afforded by the emulsion latitude and choice of constants. If such a system is to operate entirely automatically, then some degree of logical control is required. Perhaps the simplest method involves switching the shutter open time in discrete steps, depending either upon the measured brightness or upon the approach of the iris diaphragm to either the fully opened or fully closed position. By either of these methods, the continuous iris control may be employed to render the system operation continuous between shutter changes. Control is only partly continuous, however, in that an adjustment is required after a shutter change. The system can be made to operate in a near continuous fashion if desired, by the addition of a more sophisticated computational technique.

CHAPTER VII

LABORATORY INVESTIGATIONS

Section 1. Development of a Standard Light Source

Upon the completion of the development of the exposure equation, Chapter II, a preliminary study of the specifications of the systems submitted for test and evaluation was performed and it was found that a light source was needed to test these units. The requirements of such a source are:

1. The light output must possess a color temperature of 5500° K.

2. The range of brightness should be variable from 10 foot-lamberts to 10,000 foot-lamberts.

3. The light source must be convergent and accommodate the angle of acceptance of the camera and the angle of acceptance of the photosensor. This means that the light source must facilitate an angle of acceptance of at least 45°.

4. The brightness of the source must remain constant, once it is adjusted to a given level.

5. The brightness of the source must be uniform when viewed in any direction, providing the source is not viewed more than 22° off the optical axis in any direction.

The first problem that must be considered in the design of such a light box is the selection of a light source that is compatible with the above requirements.

The basic sources of electric lights are:

1. Carbon Arc Lamp

2. Electric Discharge Lamp

3. Incandescent Lamp

The carbon arc lamp will meet the color temperature requirements of the light source; however, this lamp has several serious limitations. When in operation, the lamp produces an irregular flicker thereby making it virtually impossible to meet requirement No. 4 of the preceding list. The other serious limitation is that the source is essentially a point source and a reflector system must be utilized to cause the light rays to be convergent. Because of the electrodes and their holders, shadows will be introduced in the pattern produced by the reflector. As a result the carbon arc lamp is not able to produce an even brightness over the test areas.

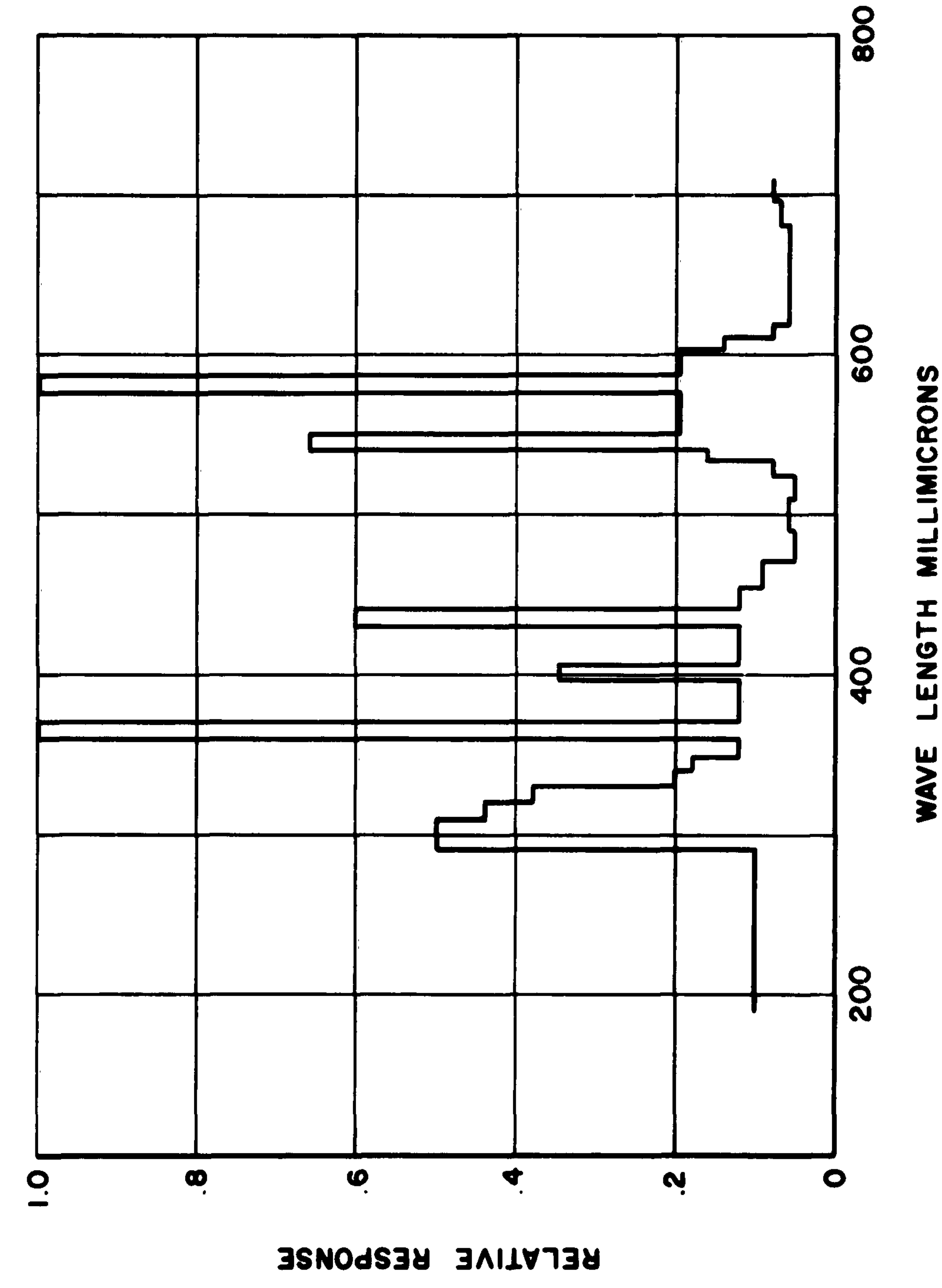
Figure 48 shows the spectral energy distribution of the Xenon-Mercury Lamp. Figure 49 shows the spectral energy distribution of a gray body radiator at 5500° Kelvin. It can be seen that Figure 48 is a very poor approximation of Figure 49. Note that much of the energy of the gaseous discharge lamp is confined to discrete wave lengths whereas in the case of a black or gray body radiator the energy distribution as a function of wave length is a smooth continuous curve. In comparison of the two Figures, one can see that the term color temperature is somewhat meaningless when applied to electric discharge type lamps. The electric discharge lamp cannot meet the color temperature requirement of the light box with any degree of precision. In addition the Xenon-Mercury Lamp presents the same problem as the carbon arc lamp in obtaining convergent light rays. The fluorescent lamp cannot, of course, meet the color temperature requirements since it has an energy distribution curve similar to Figure 48 and does not have a high light output. The physical size of the lamp also makes it extremely difficult to obtain an even convergent source of light.

From the above discussion and preliminary testing of both the arc lamp and fluorescent lamps, use of the incandescent lamp was selected as a method of obtaining the source of light for the light box.

The incandescent lamp has one serious limitation, in that it cannot produce the light at the required color temperature. Since the melting point of tungsten is 3655° Kelvin (which is the highest melting point of all metallic elements), the color temperature of light from a tungsten filament must be less than 3600° K. This limitation can be corrected by the use of color temperature filters.

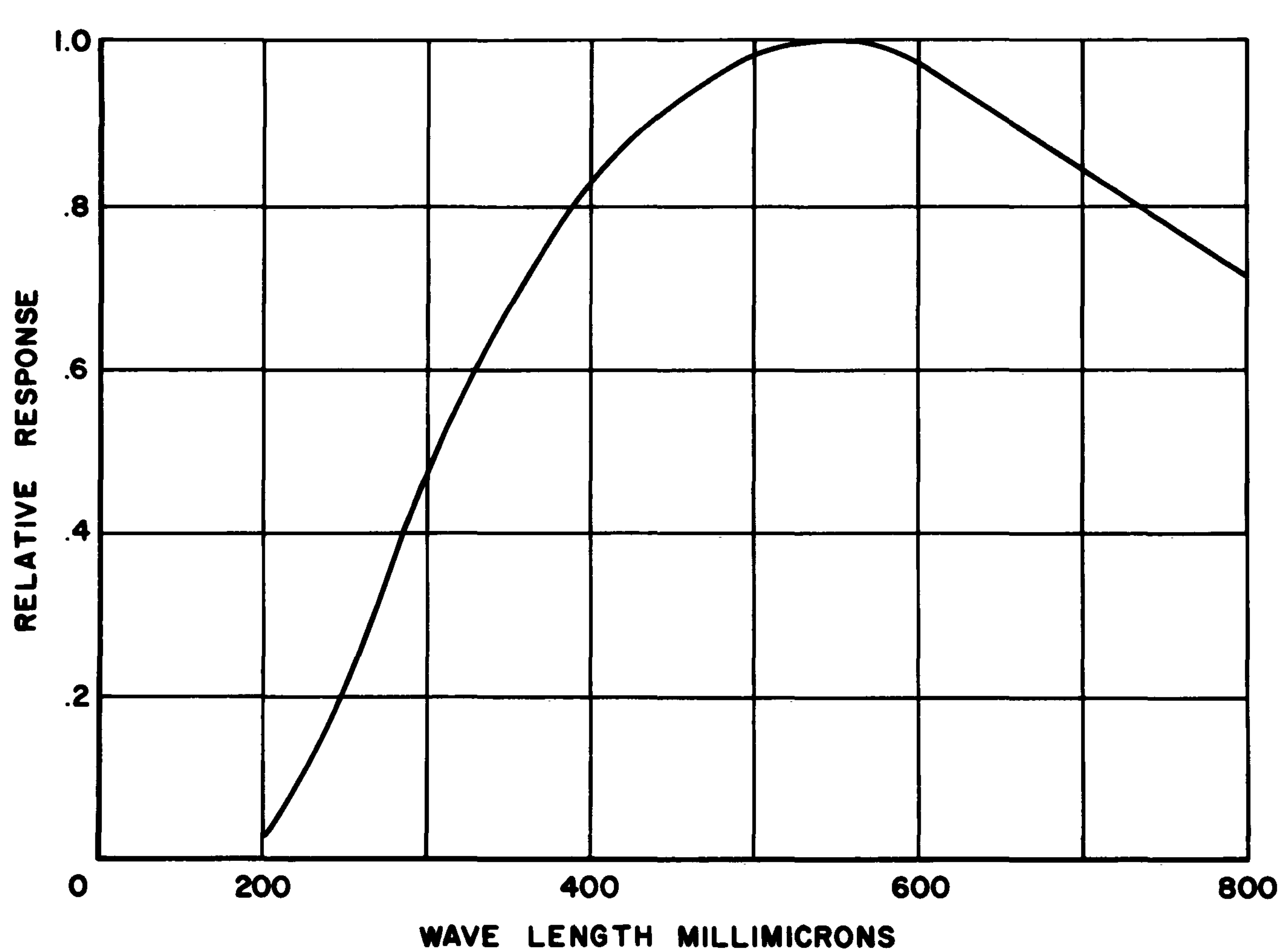
From a superficial evaluation of light in general, it may appear that the brightness of an illuminated surface may be raised to any desired light level by merely concentrating more light upon the surface from more sources. The maximum value of the brightness of a surface is limited by the actual brightness of the lamps used to illuminate the surface. The brightness of the surface can never be brighter than the source itself. Therefore, in the selection of the incandescent lamps, it is necessary to secure lamps that are of a high intensity, such as a projector type flood lamp or spot lights.

The first attempt to obtain the desired scene brightness of 10,000 foot lamberts incorporated the use of a projection type lamp and a parabolic reflector. The light source was moved beyond the focal point of the parabola causing the light rays emanating from the parabola to be convergent. The angle of convergence was adjusted by moving the lamp until it was equal to the desired angle of acceptance. The color temperature and light amplitude were adjusted using color temperature filters and neutral density filters respectively. However, since the light source has a color temperature of 3200° K, the filter required to give the proper color temperature yields a transmission less than 30% thereby



SPECTRAL ENERGY DISTRIBUTION, XENON-MERCURY LAMP

FIGURE 48



SPECTRAL ENERGY DISTRIBUTION,
5500° KELVIN GRAY BODY RADIATOR

FIGURE 49

requiring an increase in the output of the lamp of 300%. This requires a larger lamp with a resulting greater deviation from a point source. The required lamps and the distortion of the parabola reflector made it impossible to obtain an even light distribution over the required angle of acceptance for the various systems to be tested. A spherical mirror was substituted for the parabolic reflector. The results of the tests indicated that for the available bulbs neither the maximum light requirement nor the even distribution of light requirement was feasible. During this time, the manufacturers of light sources were contacted. One manufacturer recommended the use of the "sealed beam" type flood lamps. A number of these lamps were purchased. Tests were performed using these lamps. This application of the lamps was unsatisfactory for the following reasons:

1. The color temperature of the lamps is approximately 2600° K. A filter to correct the color temperature from 2600° K to 5500° K is required.

2. The pattern of the filament and front lens of the sealed beam lamp yields an uneven distribution of light on the test area.

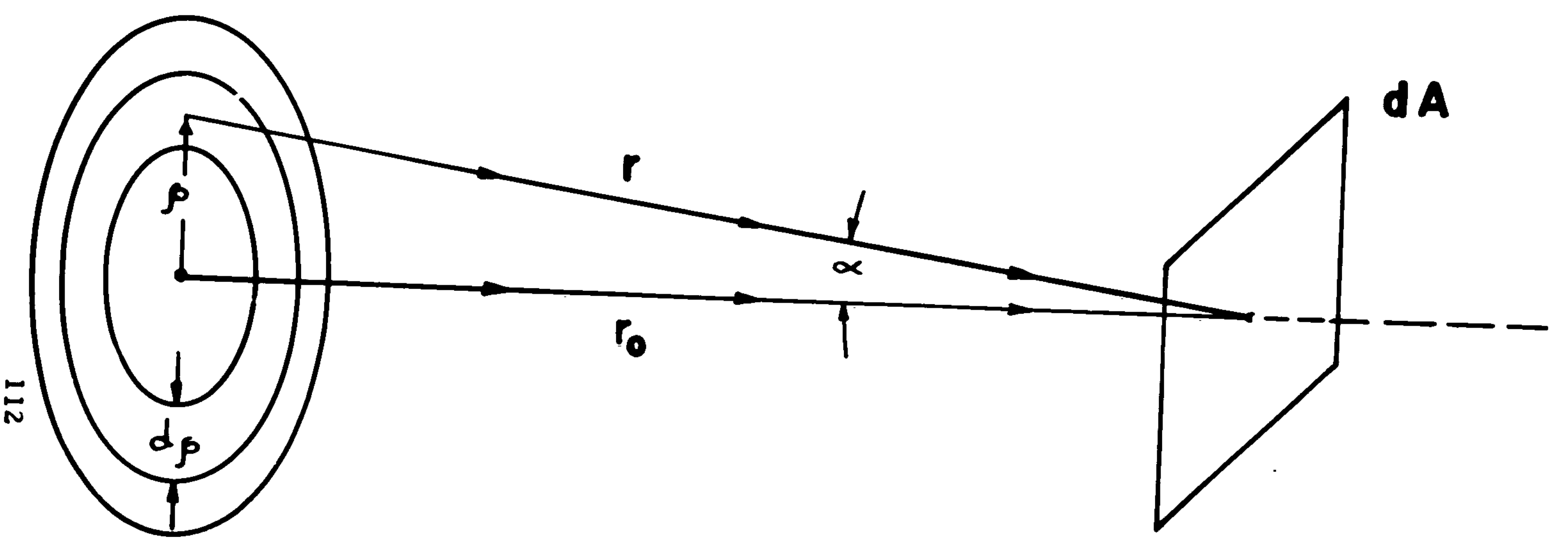
3. The amount of light per unit volume is low in comparison to the other sources of light. This means that it is very difficult to attain the lamp brightness level on the test area.

Because of the above limitations, use of the sealed beam type lamps was abandoned. Work was continued on the fabrication of a suitable light box since all measurements and test performed on the automatic exposure control system are solely dependent upon this device. It is necessary that the simulated scene brightness meet the five requirements stated at the beginning of this section.

Another method that was investigated was that of using movie projector type lamps mounted behind a diffusing medium. An arrangement of this sort will result in a source of rays emanating from the front of the diffusing medium approximately obeying Lambert's Cosine Law. If in the initial set up, the projection lamp is mounted at least eleven inches behind the diffusing medium, the test area of the light box will have the same amplitude of the light (within 95%) at the outer radius as the center provided that the radius is restricted to 3.5 inches. However, with an arrangement of this type, it is necessary to calculate the actual illumination on the light sensor due to the simulated scene brightness since the sensor has an angle of acceptance of less than 15° (half angle of view).

This illumination on the front surface of the photocell can be determined using the following formula and Figure 50.

$$E = \frac{1}{r^2} \int\int B \, dS = \frac{1}{r^2} \int B \, 2\pi\rho \, d\rho \qquad (85)$$



CALCULATION OF PHOTOCELL ILLUMINATION
FIGURE 50

where

B - brightness on the surface of the light box circular test area

dS - an element of area

Expressing ρ in terms of r, α

$$\mathcal{E} = \int_0^{\alpha} \frac{B\, 2\pi r^2 \sin\alpha \cos\alpha}{r^2}\, d\alpha = \pi B \sin^2\alpha \Big|_0^{\alpha_1}$$

which reduces to

$$\mathcal{E} = \pi B \sin^2\alpha \qquad (86)$$

Since α for all control systems being investigated is approximately 15°, let us calculate the conditions for $\alpha = 15°$.

$$\mathcal{E} = 0.211\, B \qquad (87)$$

When B is expressed in candles per sq. ft. then, $\mathcal{E}$ the illuminance, has the dimensions of lumens per sq. ft. The calculations in Chapter VI, Section 3 show that the illuminance of the photosensor for a sky brightness of 10,000 foot-lamberts is 860 lumens per sq. ft. The brightness on the front surface of the test area must be

$$B = \frac{\mathcal{E}}{0.211} = \frac{860}{0.211} = 4070 \text{ CANDLES/FT}^2 \qquad (88)$$

Expressing B in foot-lamberts rather than candles/sq. ft.

$$B = \pi(4070) = 12{,}800 \text{ FOOT-LAMBERTS} \qquad (89)$$

Since the test area must be at 12,800 foot-lamberts, the brightness of the source must be greater because of the losses that occur in diffusing the light and correcting it to the proper color temperature. Each diffusing medium gave a light transmission of 50% and two diffusing media were required to obtain a proper light pattern. The filter to correct the color temperature from 3200° K to 5500°K yielded a transmission of 30%. The total transmission of the light is 0.075 when both the diffusing media and color temperature filters are inserted. If a brightness of 12,800 foot-lamberts is required on the test area then the brightness of the light in front of the diffusing medium and color temperature filter must be at least 171,000 foot-lamberts.

From the results it can be seen that a method of this type is not satisfactory since it requires extremely high light output from a small light source. It can also be concluded that if the light were projected on a diffusing surface rather than transmitted through several mediums a much lower brightness of the light source would be required. It was this concept that brought about the development of a suitable light source.

The shortcomings of the above methods were reduced by developing a method that incorporated the following features:

1. The selection of a movie projector type lamp that has a built-in reflector. This bulb must have a high source brightness.

2. The system must incorporate the use of the lamps to project the light on a diffusing surface of a curved reflector rather than diffusing by passing the light through a diffusing medium.

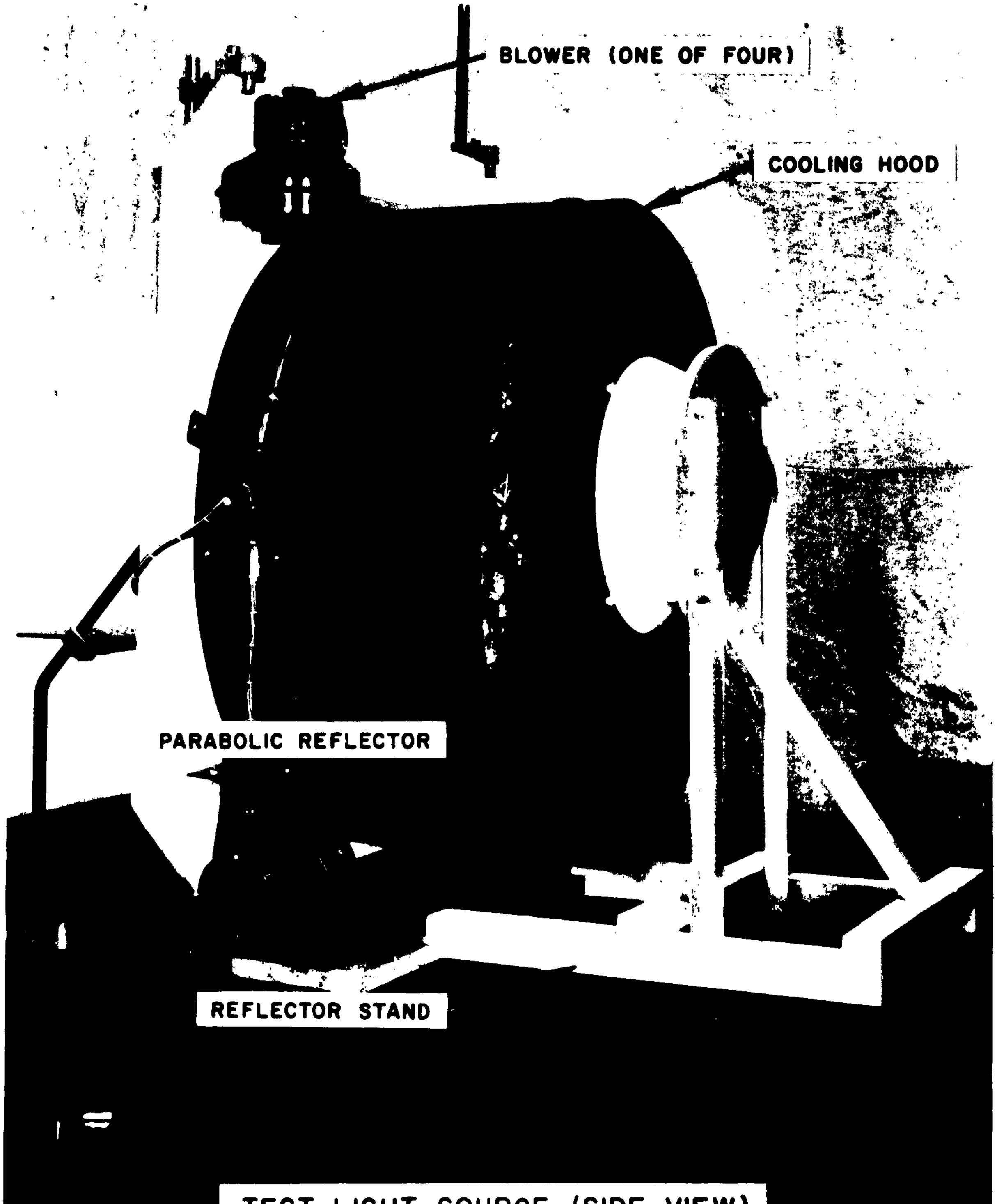
The projection lamps were spaced uniformly around the parabolic reflector. Each lamp was then individually focused to yield even illumination on the inner surface of the reflector. The inner surface of the reflector was coated in a manner such that it became a diffusing surface. The total number of lamps used was thirty-two.

When the lamps are operated at 115 volts (rated lamp voltage is 120 v), the brightness on the surface of the diffusing reflector is greater than 50,000 foot-lamberts. When the proper color temperature filter is in the view area, then the brightness at the test area is 12,000 foot-lamberts at a color temperature of 5500° Kelvin.

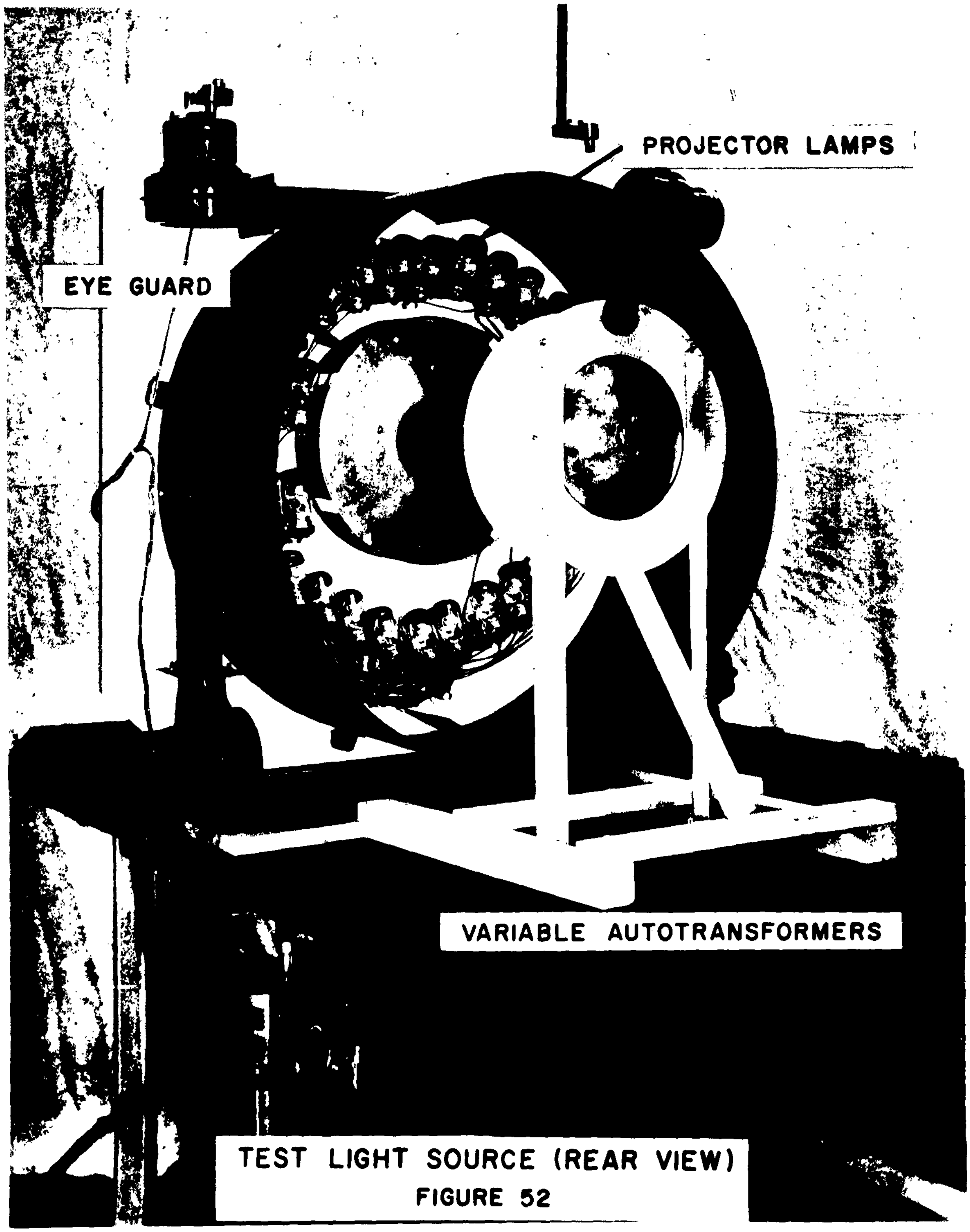
The light box in its final design utilizes two color temperature filters. One of these filters is used when the lamp voltage is approximately 95 volts. Operating the lamps at 95 volts increases the lamp life considerably while permitting light measurements to be made at brightness levels as high as 6000 foot-lamberts. The other filter is used when the lamps are operated at 115 volts. Under this operating condition, light measurements can be made at brightness levels as high as 11,000 foot-lamberts.

Calibration of the "light box" is accomplished in the following manner: First, the proper color temperature filter for the desired brightness level is inserted in the view area. Then the lamp voltage is adjusted so that the light (with the filter incorporated) has the proper color temperature. The intensity of the light is adjusted using neutral density filters. There are two sets of neutral density filters. One set varies in density in increments of 0.3. This alters the brightness by a factor of two. The fine adjustment of the brightness is accomplished with the use of the second set of neutral density filters. The density of these filters vary in density in increments of 0.04. This will result in a change of brightness in increments of 10%. Calibration is achieved by adjusting the lamp voltage for the proper color temperature. The neutral density filters are then inserted so that the light meter reads the proper level. The source is then calibrated. The light source can be adjusted to any value within 10% of the desired brightness level by merely inserting the proper neutral density filters.

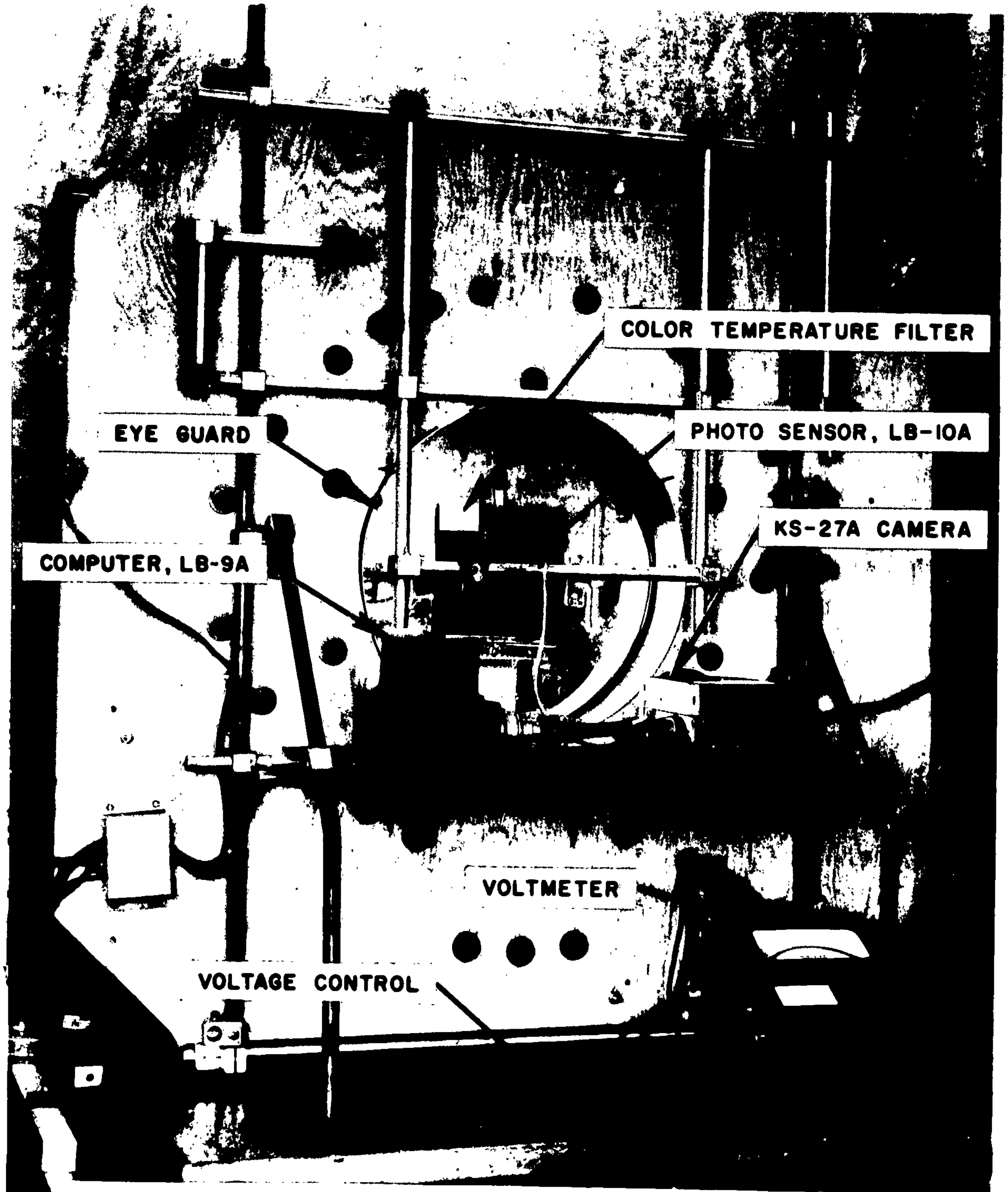
Figures 51, 52, and 53 are photographs of the light box and its component parts. With this light box, it is possible to test any system that utilizes an acceptance angle of less than 40° full angle. The parabolic reflector can be removed and other reflecting surfaces used to obtain various reflection patterns.



TEST LIGHT SOURCE (SIDE VIEW)
FIGURE 51



TEST LIGHT SOURCE (REAR VIEW)
FIGURE 52



TEST LIGHT SOURCE, KS-27A CAMERA UNDER TEST
FIGURE 53

CHAPTER VII

LABORATORY INVESTIGATIONS

Section 2. Evaluation of Two Air To Air Prototype Systems

Two prototype systems were subjected to testing under the present program in order to determine the degree of acceptability of the prototype design. Figure 54 is a photograph of System "A" installed on an N-6 Gun Camera. The photosensor is mounted directly to the camera and the amplifier assembly is separately mounted. Figure 55 is a basic circuit diagram of System "A", and assuming that the system is initially in equilibrium, the following operations occur as a result of a sudden decrease in scene brightness:

1. The current of the photocell decreases

2. This decrease in photocell current results in the meter relay moving to position #1.

3. When the armature of the meter relay is in position #1, the 22 volt supply is impressed across the "iris open" power relay circuit.

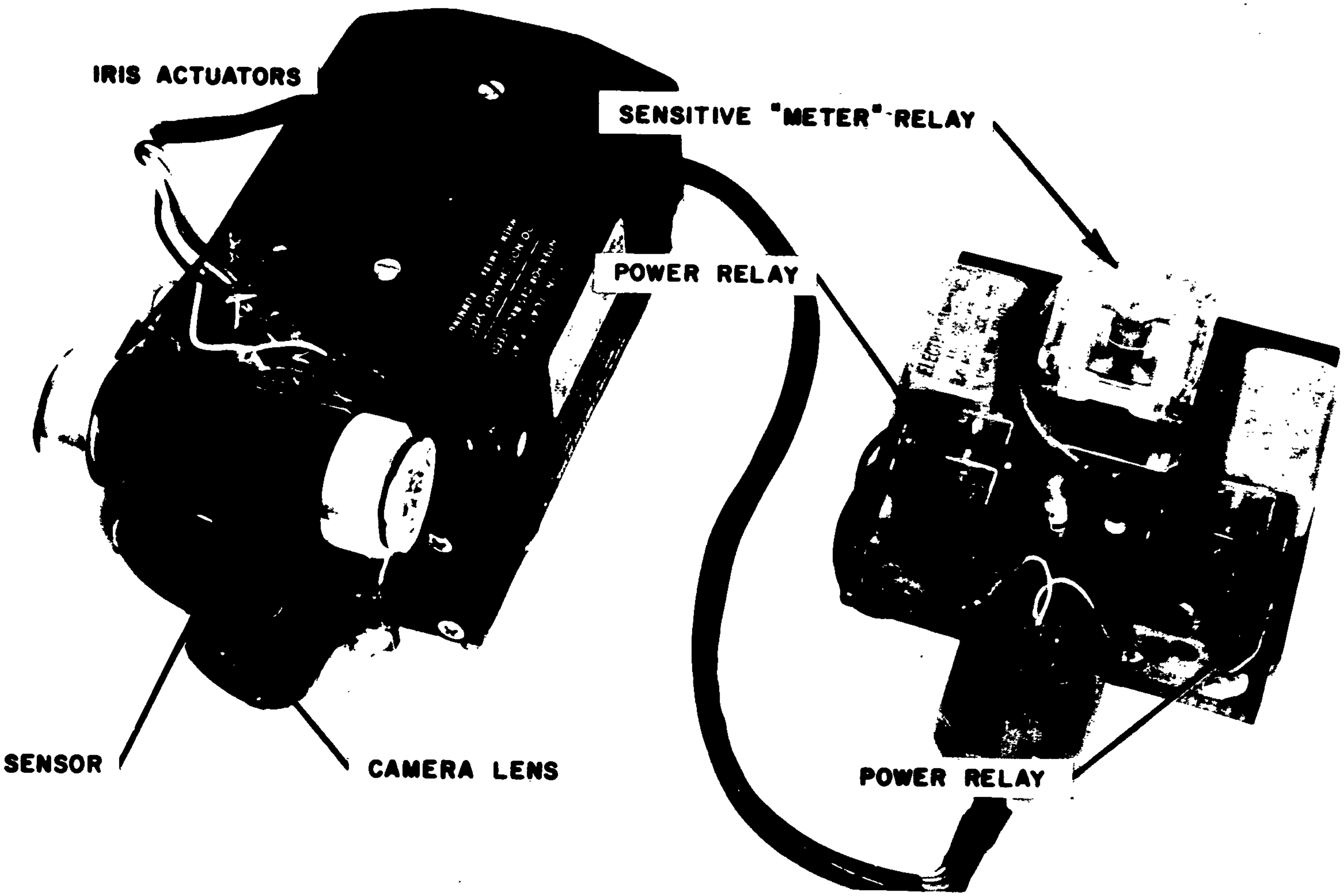
4. Energizing the power relay circuit with the 22 volt dc supply causes a series of square waves (positive amplitude) to be impressed across the iris open actuator.

5. The actuator continues to open the aperture of the photocell (and camera) until the photocell current is sufficient to pull the meter relay armature away from the contact position #1.

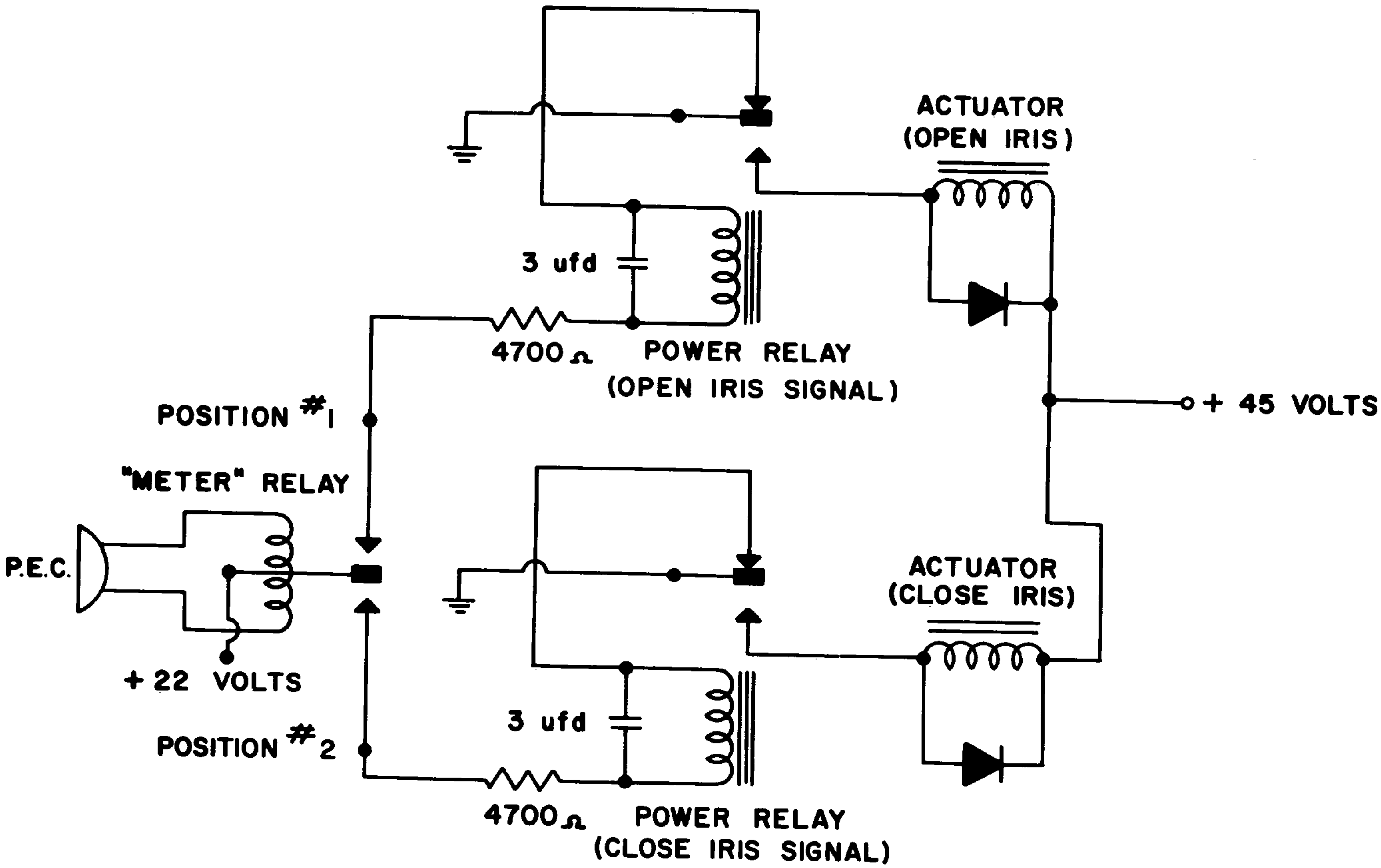
6. The system is then in equilibrium when the photocell current is large enough so that the relay armature does not make contact with either switch position.

The same procedure occurs when the brightness increases except that the meter relay is in position #2 thereby actuating the "iris close" power relay and actuator.

The response time of the system is primarily controlled by the power relay circuit. When a 22 volt dc signal is applied through the 4700 ohm resistor, a current flows and the capacitor shunting the relay coil is charged. When the voltage across this 3 mfd capacitor reaches a prescribed level, the relay pulls in and the iris actuator is energized. When the relay operates,the ground connection is opened and the capacitor proceeds to discharge through the power relay coil. When the capacitor voltage drops to a value insufficient to maintain the relay open, the contacts close, the ground connection is applied, and the process repeats. A series of periodic unsymmetrical dc pulses is, therefore,



EXPOSURE CONTROL SYSTEM "A"
FIGURE 54



AEC SYSTEM "A" SCHEMATIC DIAGRAM

FIGURE 55

applied to the iris actuator coil, and the period of this wave is clearly a function of the circuit constants. Direct mechanical coupling between the camera iris and that of the sensor is employed to complete the feedback loop.

It should be noted that this system possesses two basic characteristics of nonlinear systems. A finite amount of time is required for the relay contacts to close; however, this time is trivial compared to the time constant of the power relay circuit. Also, the system requires a change in the brightness level by a factor of approximately 25 in order that a change in iris setting results. This dead zone is the result of the relative sensitivity of the photocell and the meter relay. At most, the desired dead zone should not be greater than 2 since this is equivalent to one "f" stop.

In the analysis of this system several serious limitations were noted:

a. The angle of view of the control system. The acceptance angle of the photosensor was measured, using a collimated point source and observing the current output of the photocell short circuited. The angle was measured with the iris at its extreme positions, f/3.5 and f/16 shown below:

f setting	Measured Angle of View	Calculated Angle
3.5	130°	135°
16	120°	124°

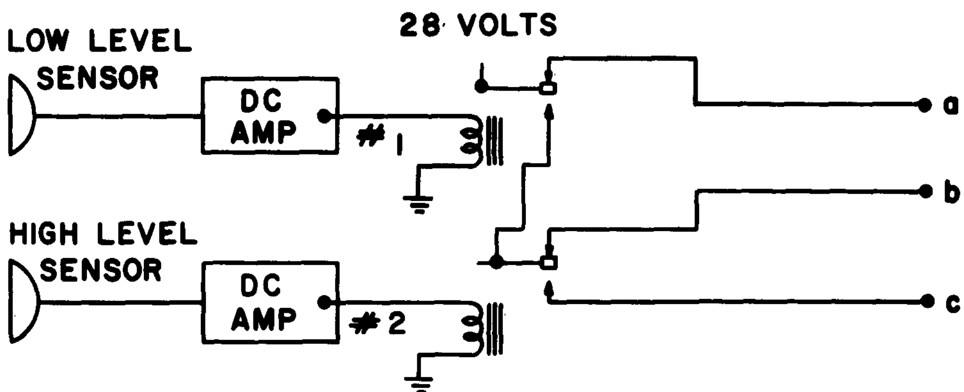
Since the system was designed to be used on the N-6 Camera using a 35 mm lens, the maximum angle of view of the camera (in a horizontal view) should be approximately 35° for the full angle rather than the angle measured. From the geometry of this system, it can be seen that the area viewed by the camera is only 2% of the total area viewed by the photosensor. (The basis for the requirement of the sensor and the camera viewing identical area was illustrated in Chapter V). Therefore, the actual area viewed by the camera has little or no control of the aperture setting thus making the system function in much the same manner as though a conventional light meter were used as the photosensor.

b. The servo loop. The sensitive relay employed is a Weston Sensitrol Model 813 "Meter" type relay. The manufacturer specifies that these relays are to be used in applications where the moving coil current changes suddenly so that the contacts close with an impact. Under normal conditions, the scene brightness will not change abruptly. Therefore, after the control system has adjusted itself to proper iris setting, the variation in the light levels will be small. Furthermore, these relay contacts actuate a set of power relays (an inductive load) which will cause additional arcing. Also, the meter relay, when subjected to

EXPOSURE CONTROL SYSTEM "B"
FIGURE 56

vibration, will exhibit contact bounce which will cause severe arcing with the inductive loading. The system controls the camera iris in terms of the brightness of the area it views with provision for the type of film or shutter speed; therefore, it serves only as a bright-hazy-dull type of control. The system did not possess the required sensitivity. This system requires a 45 volt tapped (at 22.5 volts) power supply which, of course, is not a standard power requirement. Because of the wide angle of acceptance, malfunctioning of the system and its lack of sensitivity no further tests were performed on System "A".

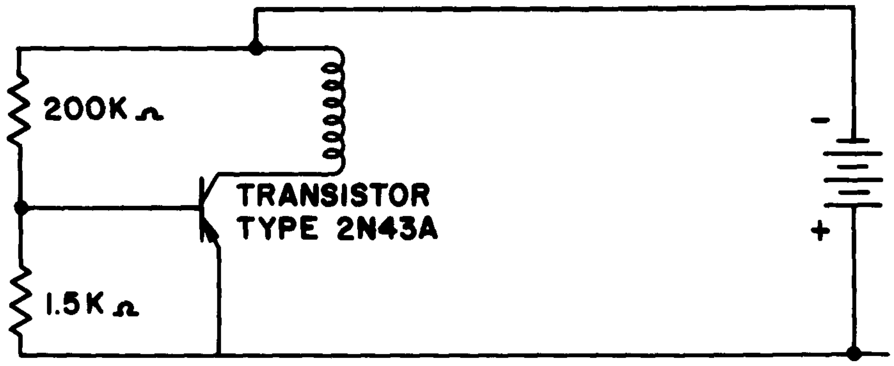
Figure 56 is a photograph of System "B". This system was designed to operate as an automatic "Bright-Hazy-Dull" controller for cameras such as the N-6 Gun Camera. The operation of this system can be explained through use of Figure 57.



AEC SYSTEM "B" SCHEMATIC DIAGRAM

FIGURE 57

When the light level seen by both photosensors is very low, the output of the amplifier is small, and + 28 volts is applied to terminal "a". As the light level of the scene increases the output of the low level sensor is amplified and fed to the relay. At some given light level relay #1 will close. A + 28 volt signal will appear across terminal "b" instead of terminal "a". If the light level is still increased, the output of the amplifier (of the high level sensor) will actuate relay #2. When this occurs, + 28 volts will be present at terminal "c". The sensitivity of the photocell and the relay will remain sensibly constant over a wide temperature range. In order to establish the stability of the amplifier gain, one must first analyze the circuit. Figure 58 shows the basic circuit of the dc amplifier used in this system.



SCHEMATIC DIAGRAM, DC AMPLIFIER, AEC SYSTEM "B"
FIGURE 58

This circuit is a single stage dc coupled common emitter amplifier and neither feedback nor temperature compensation is employed. As one might predict, the circuit is marked by sensitivity variation as a function of temperature variation. Figure 59 shows the relative current gain of the amplifier as a function of temperature with gain being normalized at the 25° level. The relative change in amplifier gain from -20° C to +80° C is 2.43 to 1. If all parameters remain constant, except temperature, the hazy or bright setting could vary by this amount.

A system of this type must be used with a camera that has provisions for a three position electric aperture control, as for example the N-9. The angle of view of each sensor was measured. They are:

1. Low level sensor - 127° (full angle)

2. High level sensor - 39° (full angle)

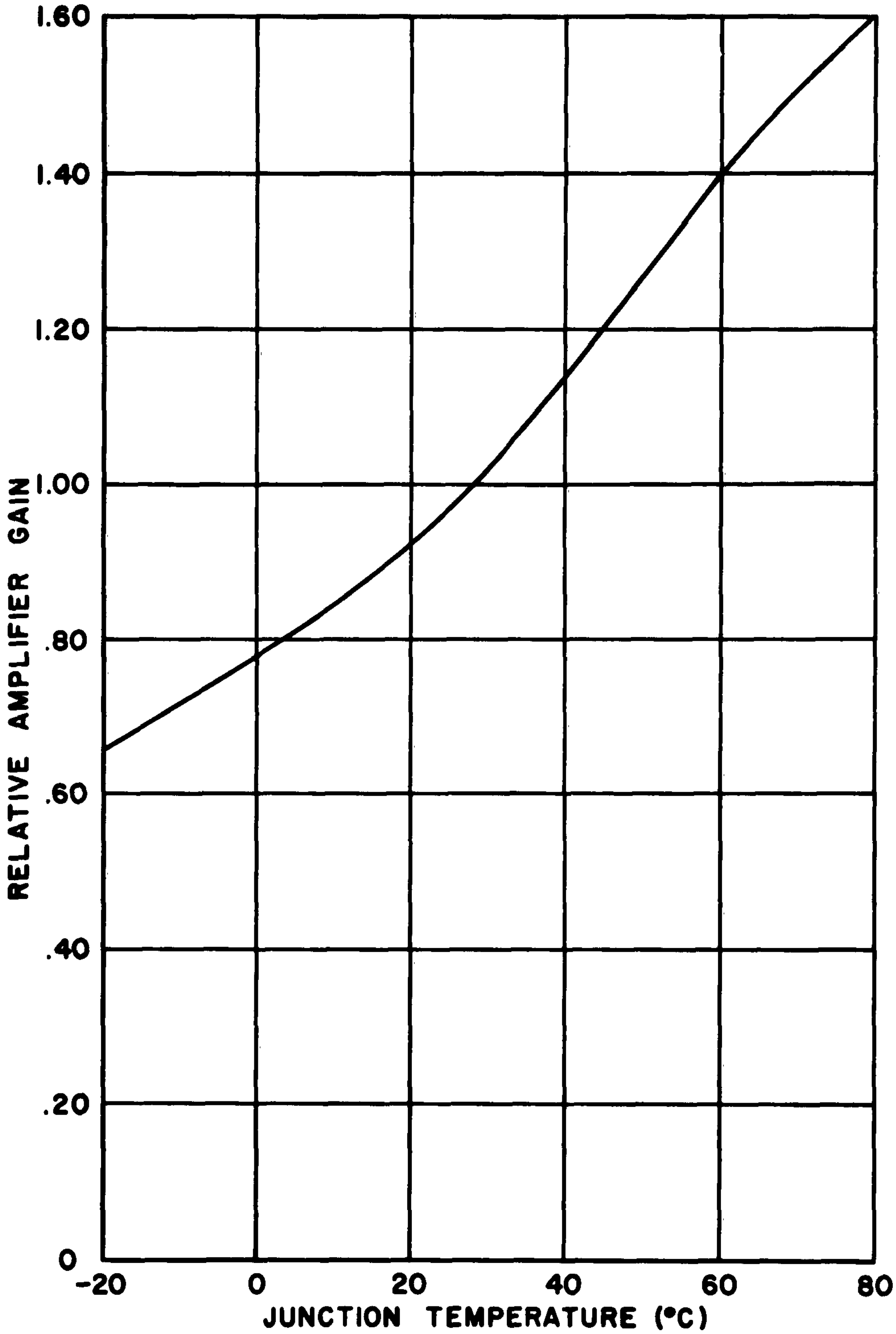
It is apparent that the sensitivity of the sensor was increased by using a wide view area since there is more active area of the photocell without the barrier to restrict the angle of view. This does not, however, control exposure as a function of the average brightness, especially for a low level of light.

This system has another serious limitation. Being an open loop system, it relies on the following factors to remain constant under all environmental conditions if the calibrations of system is to be maintained:

1. Sensitivity of photocell

2. Gain of amplifier

3. Sensitivity of relays



CURRENT GAIN OF AMPLIFIER VS TEMPERATURE
SYSTEM "B"
(NORMALIZED TO 25°C)
FIGURE 59

In summing up the work that was performed in analyzing these systems, it should be said that neither System "A" nor System "B" approximated the proper angle of view. Both systems are examples of rather basic approaches to automatic exposure control and neither sensor approximated the film response as well as that used on the KS-27A System discussed in the following section.

CHAPTER VII

LABORATORY INVESTIGATIONS

Section 3. The KS-27A System

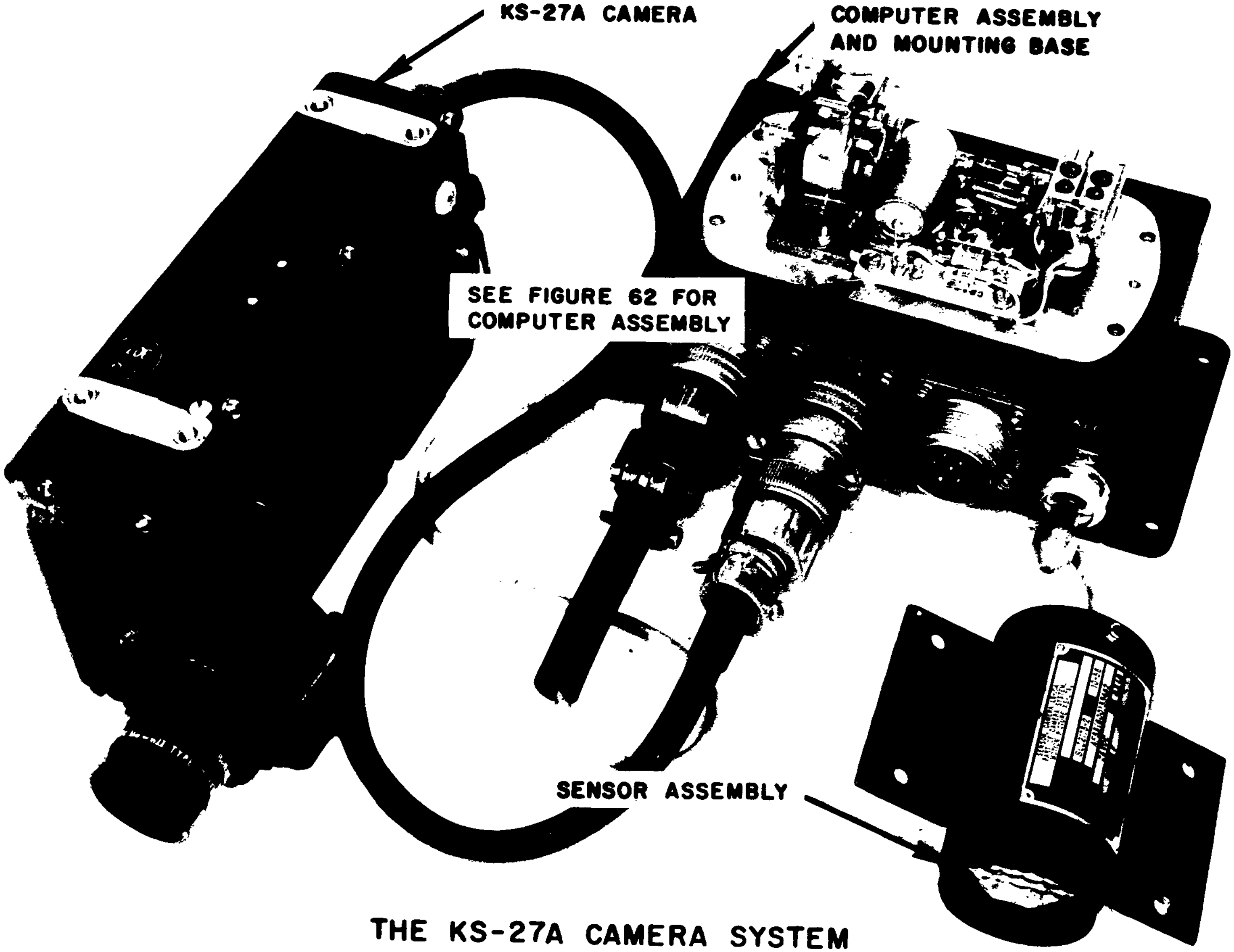
The complete KS-27A Camera System is shown in Figure 60. Figure 61 shows a view of the computer assembly and its component parts with the cover removed. Testing and analysis of the KS-27A Camera System Exposure Control was initiated with a study of the schematic diagram shown in Figure 62. Operation of the circuit can be explained in the following manner. The system utilizes two relays connected in tandem with a time constant to produce a square wave of 28 volts peak. The time duration of both the positive and negative square wave pulses are controlled by the current in the auxiliary winding of the polarized relay. This current is furnished by the unbalance of the bridge circuit when the light level changes and the servo loop has not yet rebalanced the bridge. The 28 volt square wave output is used to actuate a dc motor whose torque is a function of the dc current only. When the light level changes, the resistance of the photoconductive cell changes and the error detecting bridge is unbalanced. This causes a current to flow in the auxiliary winding of the polarized relay. This causes one of the square wave pulses to be of longer duration than the other. The resultant dc current causes the motor to drive the potentiometer slider arm until the resistance of the potentiometer is the same as the photoconductive cell. The bridge is then rebalanced and there is no dc current since both durations of the square wave pulses are the same. The servo loop of this control system can be subdivided into three sections.

1. The error detecting bridge
2. The square wave oscillator circuit
3. The feedback circuit

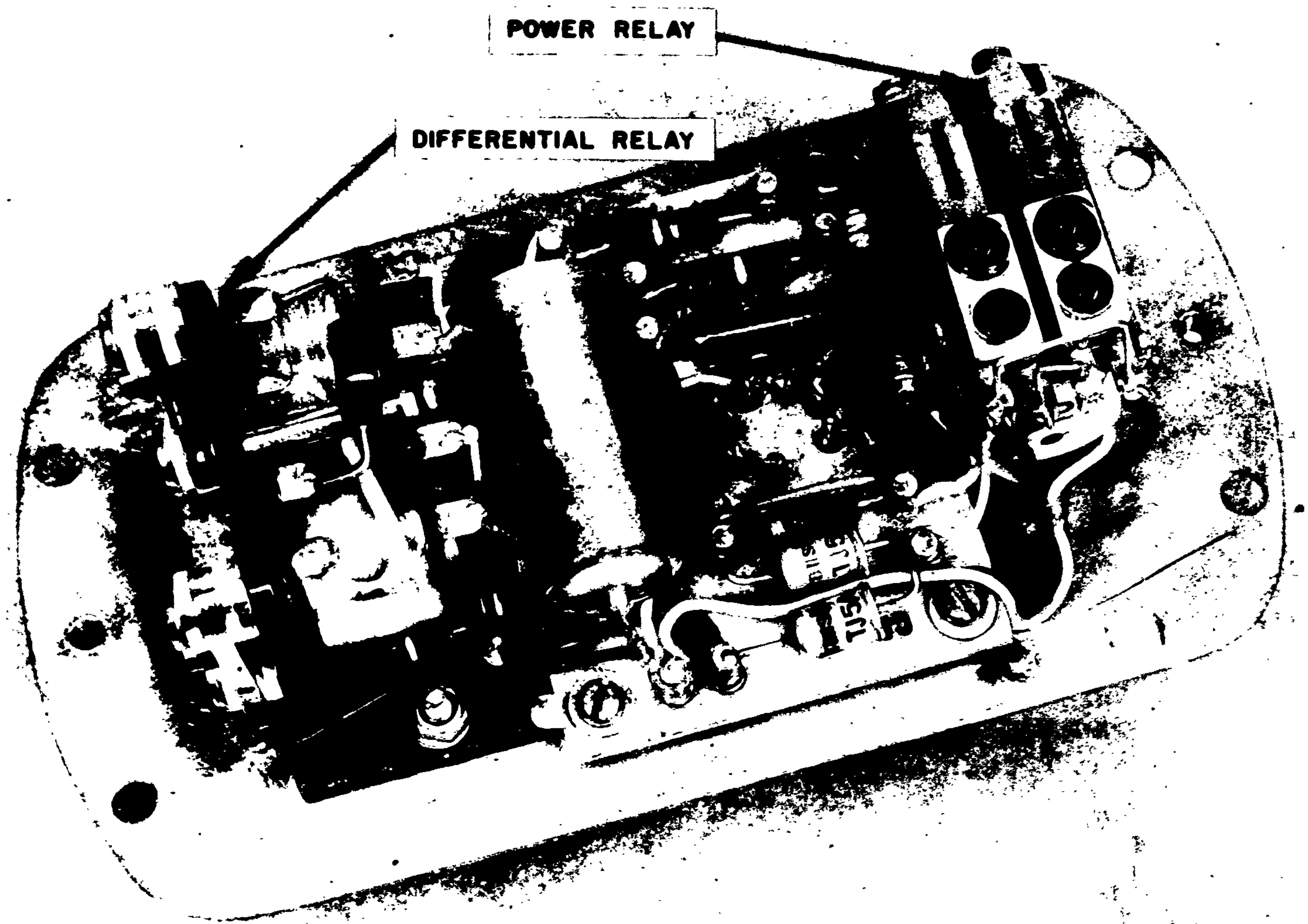
1. The error detecting bridge:

Figure 63 shows the basic circuit of the error detecting bridge where the following apply:

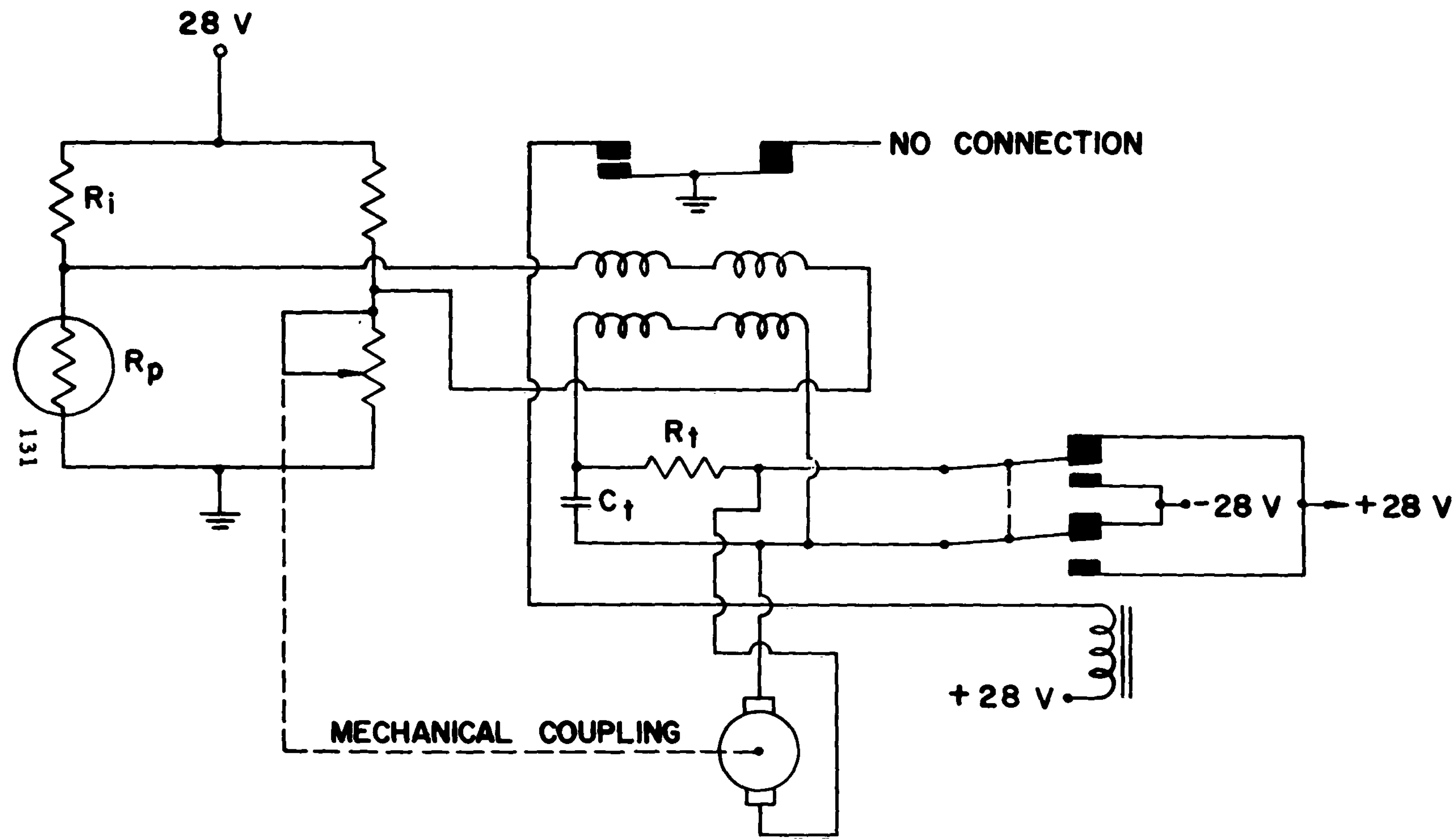
R_1, R_2	Fixed resistors
R_e	Potentiometer mechanically coupled to shutter assembly driven by servo motor
R_p	Photoconductive cell resistance, a function of light level



THE KS-27A CAMERA SYSTEM
FIGURE 60

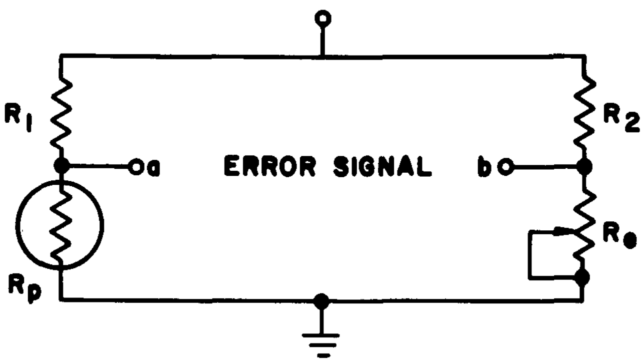


THE COMPUTER ASSEMBLY WITHOUT COVER
FIGURE 61



BASIC SCHEMATIC DIAGRAM, KS-27A

FIGURE 62

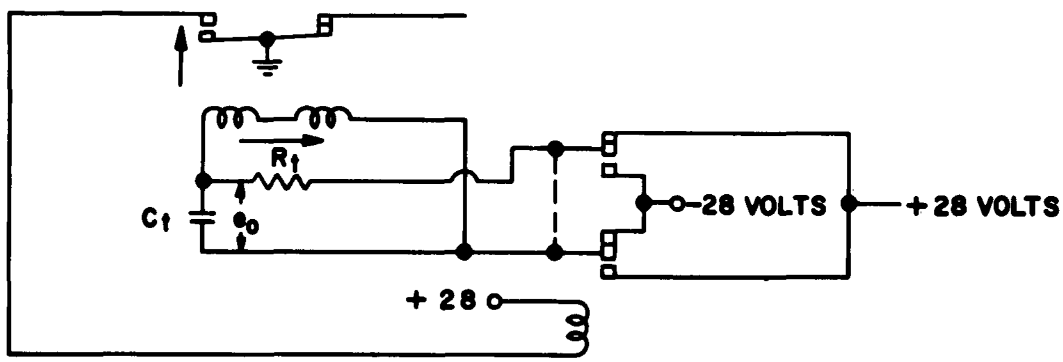


BASIC CIRCUIT OF ERROR DETECTING BRIDGE
FIGURE 63

This circuit is the basic "wheatstone bridge" circuit where R_p is a function of the light level and R_e is adjusted so that $\frac{R_1}{R_p} = \frac{R_2}{R_e}$ for balance. The error signal appears at terminals a and b.

2. The square wave oscillator circuit

Figure 64 shows the basic circuit of the square wave oscillator circuit.



BASIC CIRCUIT OF SQUARE WAVE OSCILLATOR CIRCUIT
FIGURE 64

When 28 volts is applied to the marked terminals, the capacitor C_t charges to a voltage e_o. At this voltage, the polarized relay actuates in the direction indicated by the arrow. This causes the other relay to actuate, reversing the polarity of the supply voltage to the circuit containing C_t, R_t, and the polarizing relay. Since the polarizing relay can now be actuated only by a voltage $-e_o$, the relay remains in the same position until a time when C_t changes to $-e_o$. At this time the polarizing relay moves in a direction opposite to that indicated by the arrow in Figure 64 and the current to the other relay is cut off. The current supplied to the polarizing relay through R_t is now reversed and the cycle repeats itself, giving a square wave output of 15 cps to the motor. It should be noted that the polarizing relay possesses an auxiliary winding which is energized by the error detecting bridge. If there is a current in this winding, the duration of the negative and positive square wave pulse will not be equal.

3. The feedback circuit

The feedback circuit consists of the potentiometer which is mechanically coupled to the shutter of the camera and the shutter motor. The potentiometer converts the mechanical movement into an electrical signal. From this it can be seen that the system is a nonlinear positional control system.

In the preliminary tests it was observed that the system possessed limit cycles at both ends of travel of the shutter aperture. The locations of the limit cycles were determined using a dial box substituted for R_p (see Figure 63) in place of the photoconductive diode in the sensor unit. The results of this test are shown below:

Position of Shutter Aperture (degrees)	Value of R_p (ohms)	Remarks
180	5420	End of travel
Start of oscillation	5110	Unstable limit cycle
End of oscillation	4440	Unstable limit cycle
92	2290	
46	1240	
23	760	
11.5	500	
5.7	450	
Start of oscillation	350	
End of oscillation	158	Also end of travel

Note that there are two definite unstable regions of the control system. These occur in the range of the maximum scene brightness and the minimum scene brightness. The most serious condition exists in the maximum scene brightness since the angular rotation of the motor to produce a given change in the shutter opening is extremely small. Inspection of the KS-27A camera indicates that the relationship between the angular rotation of the aperture drive motor and the motion of the shutter aperture is approximately a square law function (the same relationship that occurs in the scale spacing of a dynamometer ac voltmeter). The possible causes for the limit cycling were investigated. As a result of this investigation, it was noted that the KS-27A Camera System Aperture Drive Assembly has considerable backlash between the drive motor and the feedback potentiometer. An arrangement of this sort will always cause destabilizing effects on any second order servo system. During the course of testing of this system, it was necessary to repair the camera by pinning the worm gear bearing in the aperture drive assembly to its seat. Several other tests were performed on the KS-27A Camera System. The angle of acceptance of the sensor was measured and the sensor film response for various color temperature light sources was studied.

The sensor angle of acceptance was measured using a collimated light and measuring the resistance of the cell as light was moved away from the optical axis. Figure 65 shows a graph of the relative response of the sensor as the collimated light was rotated away from the optical axis.

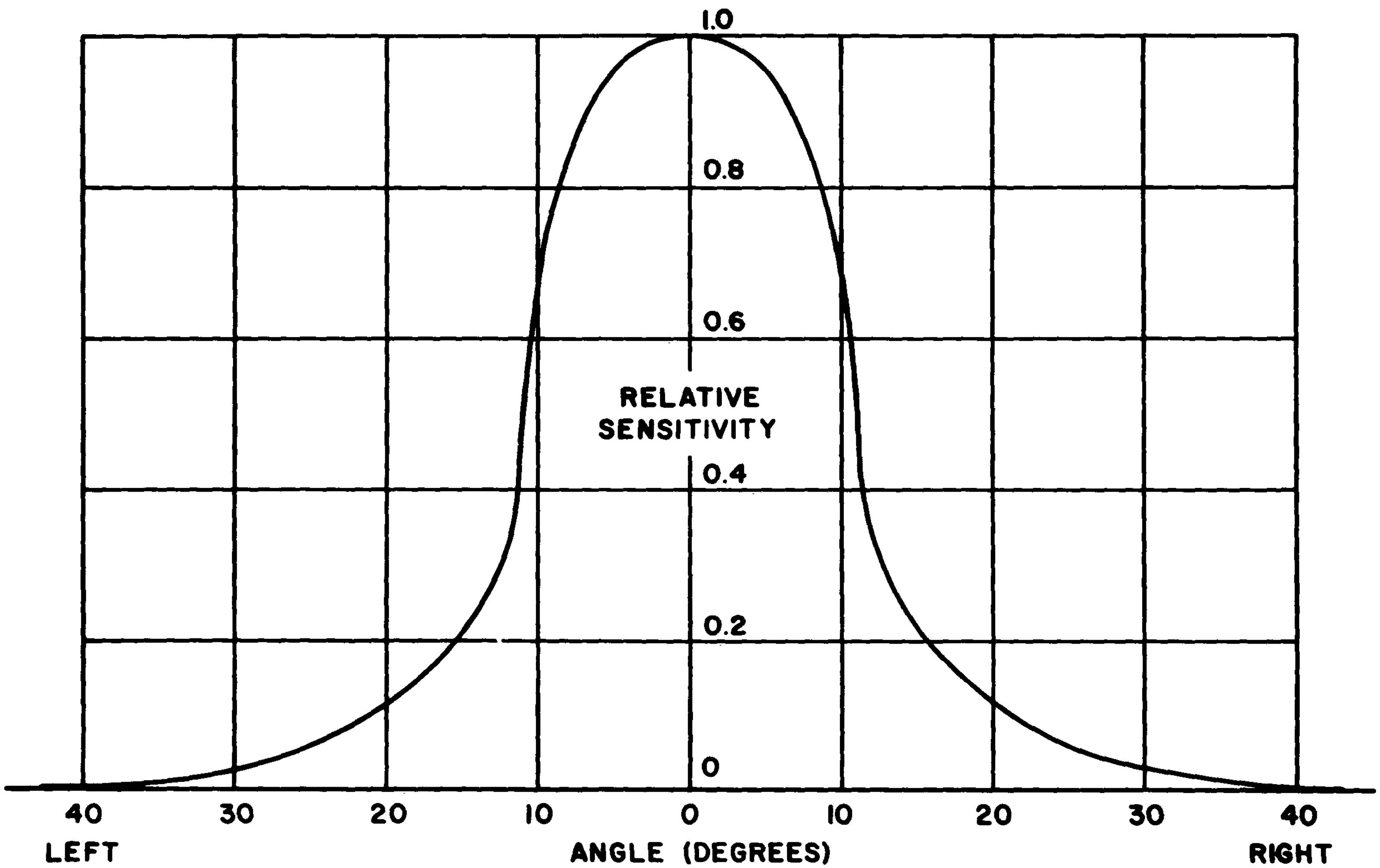
The relative response of film and the photoconductive diode used in the photosensor was determined as reported in Chapter IV Section 2.

The results of these calculations are shown below for convenience:

Color Temperature (Degrees Kelvin)	3000^{o}	$18,000^{o}$
The relative change in sensitivity of the sensor film ratio with respect to a color temperature of 5500^{o} Kelvin	.786	1.16

The above data indicates that when this film/photocell combination is used in taking pictures with a light source of $3000\,^{o}$K, the film will be underexposed by 21% or have a density of 0.08 less than the desired value (provided all other factors are correct). If the system is used for obtaining pictures with a light source of $18,000\,^{o}$K, the film will be overexposed by 16% or the density will be 0.065 greater than the photocell at this color temperature.

In Chapter V of this report, the requirement of sensor stability was pointed out and a graph of relative sensitivity of the cell used in the sensor of the KS-27A System was given. It is of interest to note that the approximate light intensity of the cell can be determined using the results of the limit cycle test and the photocell manufacturer's data sheet of this photocell. The limit cycle tests shows that the resistance of the photoconductive diode is always less than 5000 ohms. From the photocell data sheet, it can be seen that the illumination of the photocell is always greater than 10 ft. candles. Figure 32 shows



LIGHT ACCEPTANCE PATTERN OF KS-27A SENSOR

FIGURE 65

that the application of this cell has sufficient light level to yield good stability over the desired range of temperature. Comparison of the various Class "A" film photosensor response characteristics of Chapter 4 reveals that the photoconductive diode used in the KS-27A (S-15 response) yields the best overall response of those tested for a color temperature range of 3000° to $18,000^{\circ}$ K.

The actual color temperature dependency of the KS-27A system was investigated by a series of tests using the light standard described in the previous chapter of this report. These tests were performed at two color temperatures, 2700 °K and 5500 °K. The procedure of test used to perform these tests is outlined below:

1. The camera was loaded with Class "A" 16 mm film.

2. The automatic exposure control of the KS-27A System was energized.

3. The light standard was then adjusted to produce 5500 °K light (by adjustment of filament voltage and color temperature filter).

4. The sensor and camera were mounted on the light standard.

5. The camera was then triggered exposing 5 seconds of the film at brightness levels of 166, 320, 650, 1300, 2600, and 5200 foot lamberts respectively.

6. The light source was then adjusted to give a light of 2700 °K color temperature.

7. Step #5 was repeated using the 2700 °K light.

Upon the completion of the above test, the film was removed from the camera and developed as per the required military specification. The density of each 5 second of the film was measured on a densitometer in 8 spots. These spots were spaced evenly over each test run. The results of this test are shown in tabular form in Table 6. Some rather important conclusions can be derived from this data. They are:

1. The error of the exposure control at the 166 foot-lambert brightness level is considerably greater than at the other brightness levels, therefore, this brightness level will not be considered in the analysis. (This error is due to the decrease in the servo forward open loop gain. Under these conditions the results will not be repeatable to the accuracy of the system at level greater than 166 foot-lamberts). However, the accuracy of the Automatic Control system meets requirements for the application.

2. When the film is exposed to light of the same brightness level but different color temperature, the difference in the density ranged from.094 to .04 less than the density of the film exposed at 5500° K. (Omitting the 166 foot lamberts reading). The theoretical calculation for this photocell-film combination computed in Chapter IV, Section 2 predicted that the density of the film would be .08 less than that exposed to 5500° K. light source.

3. The density of the film exposed at 5500° K when over the given brightness range of 5200 foot-lamberts to 166 foot-lamberts varies as much as .2. The density of the film exposed to a light source of 2700° K over the specified brightness range varied .067 max. This tells that the change in the exposure due to a color temperature change is less than the maximum error that exists when the brightness changes. From this data it can be seen that for all practical purposes a normal light source of 2875° K could be used to test this camera system and exposure control without appreciable error in the test data.

The KS-27A System utilizes a differential polarized relay that is subject to mechanical vibration. Since any object in itself has a natural resonant frequency, the system may malfunction when the object is excited at this natural frequency. A certain amount of maintenance is required on the contacts of the two relays. At present, due to the limit cycle, the system cannot meet the requirements of the KS-27A Specification. The specification requires that no continuous oscillation be present in the system during its operation.

TABLE 6

KS-27A TEST RESULTS

Brightness In Ft. Lamberts	2700° K LIGHT SOURCE FILM DENSITY								Average
166	.68	.65	.64	.65	.615	.655	.64	.645	.648
324	.68	.68	.70	.695	.695	.695	.68	.68	.689
650	.74	.70	.725	.71	.70	.71	.70	.73	.715
1300	.74	.705	.70	.70	.73	.75	.72	.72	.721
2600	(.90)	.70	.73	.72	.70	.69	.72	.72	.711
5160	.74	.70	.71	.70	.70	.70	.715	.735	.715
	5500° K LIGHT SOURCE FILM DENSITY								Average
166	.60	.60	.61	.60	.61	.595	.60	.60	.603
324	.73	.74	.72	.72	.73	.72	.74	.73	.729
650	.75	.76	.75	.76	.77	.75	.73	.75	.753
1300	(.88)	.76	.78	.77	.78	.77	.79	.77	.774
2600	.84	.80	.80	.80	.80	.80	.81	.82	.805
5160	(.86)	.78	.79	.82	.80	.81	.80	.80	.800

Numbers in parenthesis were not used to compute average. Higher density of these readings are due to initial acceleration of shutter blade and do not represent steady state conditions.

CHAPTER VIII

EVALUATION METHODS & STANDARDS

Guidelines for Performance Evaluation:

The performance of an automatic exposure control system is ultimately judged by the consistency of exposure obtained over a wide range of lighting conditions. Inasmuch as it is not possible to predict and simulate all sets of circumstances, there is a need for a standard set of test criteria upon which to base laboratory and field evaluation. As we have pointed out repeatedly in preceding chapters, the photographic process, in the general sense, is not readily amendable to absolute engineering methods. For this reason, any application of automatic exposure control must be based on the operational conditions which establish the need. Once these conditions are defined and specified, then the evaluation procedure adopted must be sufficient to establish specification compliance. In many cases, notably those involving aerial photography, sufficient experience has been accumulated to permit the formulation of an adequate control equation. In others the system constants must provide the necessary latitude to accommodate experience on a cumulative basis. In the preceding chapters, we have attempted to describe the variables involved in the problems and to indicate some approaches which may be used. In the present Section, some general information regarding recommended steps in the engineering evaluation of such systems will be presented. For simplicity, it will be assumed that environment qualification with respect to vibration, shock etc., is accomplished in accordance with appropriate specifications either separately provided or derived from knowledge of the expected operating conditions.

The Exposure Control System consists of four generalized functions. These are:

1. The brightness sensor
2. A simple computer which accepts constant inputs (and perhaps other information) and supplies reference to an error signal producing mechanism.
3. An electromechanical controller which may take the form of a servo system.
4. Such auxiliary equipment as is required, including the secondary power supply.

Generally speaking, the requirements of the photographic process will be satisfied if

a. The field of view of the sensor corresponds to that of the camera. In some cases, other requirements may allow a specific area of maximum interest to be chosen and observed with a sensor having a smaller field of view than the camera). Such situations depend largely on fixed scene configuration and are not of the most general type.

b. The relative output of the sensor as a function of light wave length closely approximates the relative response of the film.

c. The automatic exposure equation is mechanically satisfied over the required range of the variables.

d. The automatic exposure solution is virtually unaffected by local environmental conditions, including temperature and primary power variations.

e. The response is sufficiently rapid, free from overshoot and oscillation, etc., to meet the requirements of the particular application.

Other considerations might include those of cost, complexity, weight, size, and other factors related to the physical configuration and the camera itself. The final proof of satisfactory design is, of course, in actual field use, after the arbitrary constants have been determined. Final use also depends on the correctness of calibration of potentiometer adjustments for film speed and time of exposure. In fact there is but one constant required for a given film and the equation takes the form

$$f^2 = K_f \, B \, t$$

since the arbitrary, numerical, and emulsion constants can be combined. Two controls are then required, and the accuracy of the solution will depend on the setting and calibration of these controls. One will often find an appreciable difference between indicated and true exposure time, for instance and the AEC "t" control must be calibrated in terms of true exposure time.

APPENDIX I

UNITS AND CONVERSION FACTORS

A. Definitions: Photometric

Radiant Flux	Power emitted by the source, measured in watts.
Luminous Flux	A representation of the total visual sensation generated by a source, measured in lumens.
Luminous Intensity	Luminous flux per unit solid angle, measured in candles or lumens/steradian.
Illuminance	Luminous flux per unit area incident upon an illuminated surface. Measured in lumens/sq. ft. is equivalent to foot candles.
Luminance:	The luminous intensity per unit area emitted by an extended source. Measured in candles per unit area, often expressed as foot-lamberts. Equivalent to brightness as employed herein.
Color Temperature	A term describing the visual spectrum emitted by a radiator. The color temperature of the radiator is the temperature to which a black body would have to be raised to produce a visual sensation equivalent to that of the radiator.

B. Definitions: Photographic

Exposure	The product of emulsion illuminance by time of exposure. Within certain limits, the deposition of metallic silver, and, therefore, density, is proportional to this quantity.
Reciprocity	The law stating the proportionality between exposure, time, and illuminance.
Density	The optical density is the logarithm to base 10 of the opacity, equivalent to the logarithm of the transparency.

C. Conversion Factor:

Multiply	by	To obtain
Foot-Lamberts	1	Foot-candles
Foot-Candles	1	Foot-lamberts
Lumens/unit solid angle	1	Candles
Lumens/sq. ft.	1	Foot-candles
Candles/sq. ft.	3.1416	Foot-lamberts
Candles/sq. ft.	3.1416	Foot-candles
Foot-lamberts	0.318	Candles/sq ft.
Foot-candles	0.318	Candles/sq ft.
Meter-candles	0.0929	Foot-candles
Candles/sq meter	0.292	Foot-lamberts
Foot-candles	10.764	Meter-candles
Foot-lamberts	3.43	Candles/sq meter
Meter-candles	0.0929	Foot-lamberts
Foot-lamberts	10.764	Meter-candles
Illuminance	seconds	Exposure
Candles/sq ft.	33.82 x seconds	Meter-candle-second
Weston Film Speed	1.25	ASA Index
ASA Index	0.8	Weston Film Speed
ASA Speed	0.25	ASA Index
ASA Index	4	ASA Speed

APPENDIX II

APPLICABLE SPECIFICATIONS AND STANDARDS

A. American Standards Association:

PH 2. 1 - 1952	Spectral Diffuse Densities of Three-Component Subtractive Color Films
PH 2. 3 - 1956	Activity or the Relative Photographic Effectiveness of Illuminants, Method for Determining the
PH 2. 5 - 1954	Photographic Speed and Exposure Index, Method for Determining
PH 2. 6 - 1954	Sprectral - Sensitivity Indexes and Group Numbers for Photographic Emulsions, Method of Determining
PH 2. 11 - 1958	Sensitometric Exposure of Daylight - Type Color Films
PH 2. 12 - 1957	General Purpose Photographic Exposure Meters
PH 2. 14 - 1958	Special - Purpose Photographic Exposure Indexes for Short and for Long Exposure Times
PH 2. 19 - 1959	Diffuse Transmission Density
PH 3. 2 - 1952	Performance Characteristics of Focal - Plane Shutters used in Still Picture Cameras Method for Determining
PH 3. 3 - 1952	Exposure - Time Markings for Focal - Plane Shutters used in Still Picture Cameras
PH 3. 4 - 1952	Performance Characteristics of Between-the-Lens Shutters used in Still Picture Cameras, Method of Determining
PH 3. 5 - 1952	Exposure-Time Markings for Between-the-Lens Shutters used in Still Picture Cameras
PH 3. 22 - 1958	Distribution of Illuminance over the Field of a Photographic Objective or Projective Lens

PH 3.29 - 1958	Apertures and Related Quantities Pertaining to Photographic Lenses, Methods of Designating and Measuring
Z 38.4.21 - 1948	Focal Lengths and Focal Distances of Photographic Lenses, Methods of Designating and Measuring

B. Federal:

L-F-330, December 17, 1956	Film, Photographic, Black and White, General Specification for

C. Military:

MIL-F-32B June 3, 1958	Film, Photographic, Aerial, Black & White
MIL-STD-150 October 23, 1950	Military Standard, Photographic Lenses
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APPENDIX III

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